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Technological change in the steel industry and its effects on environmental footprints of downstream products

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MASTER THESIS

for

Student Birgit Furseth Karlsen

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Technological change in the steel industry and its effects on environmental footprints of downstream products

Teknologiendring i stålindustrien og dens effekt for fotavtrykket til produkter produsert med stål

Background and objective

The production of steel is a highly emission and energy intensive industrial process. Steel is present in many industries and products which makes it very influential when it comes to the carbon footprint of downstream products. There are two main technologies for making steel, the integrated blast furnace and basic oxygen furnace (BF/BOF) and the electric arc furnace (EAF). In addition, the open-hearth furnace (OHF) is used in Russia and Ukraine. If the technology used today where to be changed to the average and the best technology, the emissions from the steel production would change and effect the emissions embodied in the downstream products.

This master thesis will first determine the energy input to the different steel technologies in the multi-regional input-output system EXIOBASE and compare them. Then, the emission data in EXIOBASE will be quality checked and its relation to energy use will be analysed. The future of the steel technologies and stock will be examined using external data sources and a literature review. The main focus of this master thesis is to do a sensitivity analysis of the steel industry to technological change, i.e. if the present technology shares are changed to the average technology, to the best available technology and to the most realistic future scenario of technologies. This will be done using EXIOBASE. The goal is to find out how this will change the emissions from products produced with steel and the emission embodied in consumption, and ultimately how this can help to mitigate climate change.

The following tasks are to be considered:

1. Determine the energy input to the steel technologies from EXIOBASE.
2. Quality check energy & emission data in EXIOBASE and compare to data found in literature. Improve as required.
3. Literature on the future of steel production. The different technology shares – how big does the EAF become and when does Russia replace the OHF.
4. Find the future steel stock predictions of primary and secondary steel.
5. Literature on sensitivity and scenario analysis in general and specifically in IO.
6. Sensitivity analysis on the downstream products connected to steel to analyse the global impact of a technological change. The sensitivity analysis will be done by replacing the steel production technologies: one where all the steel production is replaced with the

average technology, one where it is replaced with the best technology and one where the technology is replaced by the most realistic scenario of technology shares based on the future steel stock.

7. Analyse various supply-chain effects including the displacement of emissions from the steel industry to other industries, e.g. electricity. Discuss link to climate policy and industrial strategy.

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

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

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

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

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

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

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

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

Department of Energy and Process Engineering, 15. January 2018

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Richard Wood
Academic Supervisor
Research Advisor: Kirsten Wiebe

Preface

This master thesis was written in the spring of 2018 during my MCs degree in Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). The paper was written at the Department of Energy and Process Engineering (EPT).

I would like to thank my co-supervisor, Kirsten Wiebe, for excellent advices throughout the writing process. Our discussions have been insightful and motivating. In addition, I would like to thank my supervisor, Richard Wood.

Birgit Furseth Karlsen
Trondheim, June 2018

Abstract

The CO_2-emissions from the steel industry is at present 2.5 Gt, which represents 9% of the worlds total carbon emissions in 2010. To keep the temperature change under 2.4°C compared to the pre-industrial time, a emission reduction of 50-85% must be achieved in the industrial sector (Allwood et al. 2010).

The integrated blast furnace and basic oxygen furnace (BF/BOF) is the most emission-intensive of two steelmaking technologies, the other being the electric arc furnace (EAF). At present, the BF/BOF industry stands for 74% of the total crude steel production (World Steel Association 2017).

Here, I show the possible global emission reduction in the future. This is done with two scenarios were the steel technology share shifts towards the EAF-route.

to correct the faulty emission-intensities of the technologies found in Karlsen (2017), a data re-allocation in the multi-regional supply-use tablewas carried out. The definition of the technologies can be altered in the use-table. Inn addition, re-allocation in the supply-table were done to adjust the technology shares.

Scenario 1: realistic depicts a realistic future leading the consumption-based CO_2-emissions from steel to decrease with 12% compared to the current data. In scenario 2: BAT, a optimistic scenario were the EAF share is set to 75%, the decrease is 33% from the current data. The global decrease of total consumption-based CO_2-emissions was found to be 3-4%. However, this is not sufficient to reach the climate goals.

The scenarios also showed a decrease in the share of the emissions and the total emissions, from steel in the other industries. The changes in percentage points were especially high in the manufacturing industries.

I therefor infer that if a bigger share of steel were made from the EAF-route, global emissions would decrease. However, more implementations and improvements of the already existing technologies must be utilised to fully realise the global emission reduction goal.

Sammendrag

Dagens utslipp av CO_2 fra stålindustrien er på 2.5 Gt, og dette representerer 9% av de totale CO_2 utslippene i verden i 2010. For at temperaturendringen ikke skal overstige 2.4 °C i forhold til nivået før den industrielle revolusjonen, må utslippene i industrisektoren gå ned med 50-85% (Allwood et al. 2010).

En kombinasjon av en masovn og LD-prosessen (BF/BOF) er den mest utslippsnitensitive av de to prosessene for å lage stål. Den andre prosessen er kalt elektrostålprosessen (EAF). På det nåværende tidspunkt representerer BF/BOF-prosessen 74% av den totale stålproduksjonen (World Steel Association 2017).

Her viser jeg mulige nedganger i de globale CO_2-utslippene i fremtiden med hjelp av to scenarioer hvor andelen av stål fra EAF-prosessen øker.

Dataendringer i de multiregionale "supply"- og "use"-tabellene måtte gjennomføres. Dette ble gjort etter feil ble funnet i Karlsen (2017) i forhold til utslippsintensiteten fra EAF-prosessen. Dette ble rettet opp i "use"-tabellen. I tillegg ble andelen av de to prosessene endret i "supply"-tabellen.

Scenario 1: realistisk viser en realistisk fremtid som reduserer utslippene fra stål med 12% sammenlignent med dagens utslipp. I scenario 2: BAT (best tilgjengelig teknologi (på engelsk best available technology)), hvor andelen stål fra EAF-prosessen er økt til 75%, er nedgangen på 33%. Den globale nedgangen er på 3-4% med scenarioene. Dette er likevel ikke nok til å nå klimamålet for industrier. Scenarioene viser også en nedgang i andelen stålutslipp i de andre industriene. Endringene i prosentpoeng i produksjonsindustriene, var spesielt høye.

Jeg konkluderer derfor med at hvis andelen fra EAF-prosessen er høyere, vil de globale utslippene gå ned. Likevel må man ha flere implementeringer og forbedringer av den allerede eksisterende teknologien for å nå utslippsmålene.

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Abbreviations

BAT Best Available Technology.

BAU Business As Usual.

BF Blast Furnace.

BF/BOF Integrated Blast Furnace and Basic Oxygen Furnace.

CF Carbon Footprinting.

DRI Directly Reduced Iron.

EAF Electric Arc Furnace.

EOL End-Of-Life.

GDP Gross Domestic Product.

GHG Greenhouse Gases.

IO Input-Output.

IOT Input-Output Table.

LCA Life Cycle Assessment/Analysis.

MFA Material Flow Analysis.

MR EE SUT/IOT Multi-Regional Environmentally Extended Supply-Use/Input-Output Table.

MR use Multi-Regional Use-Table.

MR EE IOT Multi-Regional Environmentally Extended Input-Output Table.

MRIO Multi-Regional Input-Output.

MRSUT Multi-Regional Supply- and Use-Table.

OHF Open Hearth Furnace.

pp Percentage Points.

SUT Supply- and Use-Table.

1. Introduction

Steel is a product that is highly incorporated into our society. The steel industry is one of the most emission-intensive industries in the world with 9% of the total CO_2-emissions (Allwood et al. 2010). In addition to this, the production of steel and steel products has increased throughout history, and this trend is not expected to change (Wanga et al. 2009). This has lead to some concern about the impact the steel industry has on the climate. In 2016 74% of the crude steel produced was primary steel from the integrated blast furnace and basic oxygen furnace (BF/BOF). This is the most emission-intensive of the two main steel technologies, the BF/BOF and the EAF.

A considerable part of the increased consumption of steel in recent years, can be seen in relation to the Chinese populations rise out of poverty. China produces almost 50% of the worlds output of steel, and 89% of this originate from the BF/BOF. The current situation in the Chinese steel industry is however dominated by the fact that the United States has implemented a tariff on imported steel from China and other countries. This circumstance has been prominent in the media, but it is the economical aspect of the steel that is the main focus. In this thesis, however, it is the environmental impact and how to improve the current situation that is the focal point. Can a change in the steel industry help mitigate global emissions?

Findings from Karlsen (2017) using the EXIOBASE database discovered some discrepancies between the literature and the results. The data showed that the emission-intensity of the EAF was higher than for the BF/BOF in a majority of the countries. These discoveries where the motivation for the work in this master thesis. To improve the results from Karlsen (2017) the energy input and the CO_2-emission intensities of the steel technologies from EXIOBASE were found. As these were examined and deemed incorrect, a re-allocation of the data was carried out.

The main focus of this master thesis is to do an analysis of two possible outcomes of the steel industry in the future and the effect this can have on the global emissions. To accomplish this, the share of the technologies were changed in the two what-if-scenarios. The first scenario was a realistic prediction of the future. Here, the results showed a decrease in the consumption-based CO_2-emission for steel at 12%. In the second scenario, 75% of the steel output was produced using the best available technology - the EAF. In this prediction, the total steel emission decreased with 33%.

The thesis starts with a deeper look at earlier literature on energy use and emissions in the steel sector in Chapter 2. In Chapter 4 the data work is presented and the reasoning for the changes in the EXIOBASE data displayed. This chapter also contains the literary groundwork for the changes made in the what-if-analysis.

After these changes are made, the results for the current data and the two scenarios are analysed and discussed in Chapter 5. Finally a conclusion and further research wrap up the paper in Chapter 6.

2. Literature summary

Iron and steel, together with cotton and coal, were the building blocks of the industrial revolution, but they have been in use for thousands of years (Remus et al. 2013). Advances in the technology has provided the industry with the ability to increase the production of steel throughout time, as Figure 2.1 shows, and the output is predicted to continue to increase in the years to come. Especially the usage of coke instead of coal that was developed in the eighteenth century, lead to a significantly higher output than previously (Remus et al. 2013). The importance of steel, and the large amount of energy the sector consumes, has led to concern on the impact this may have on the climate (Wanga et al. 2009). The steel industry stands for 9% of the global carbon emissions at 2.5 Gt of CO_2 (Allwood et al. 2010). This equals almost 600 million round-trips from New York to Tokyo (myclimate n.d.). In 2006, 94% of the emissions from the steel industry came from the ten countries with the largest production (Newman 2010).

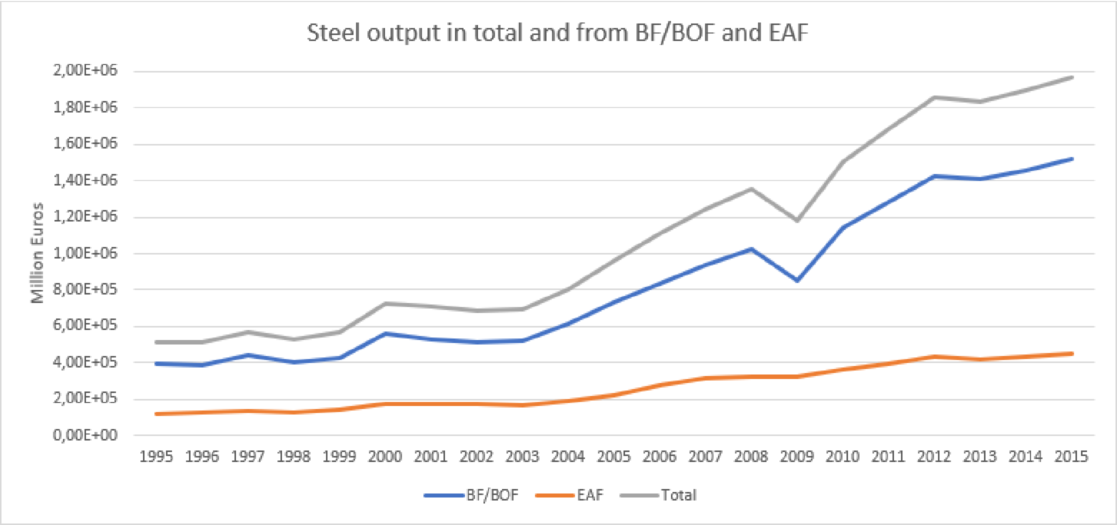

Figure 2.1: The output in million € from all EXIOBASE countries from 1995-2015. The calculation can be found in Appendix A.4.1.

It is China that has the highes increase in steel production and use. In 2006, 33% of the steel produced world wide was from China. In 2016, this number had increased to almost 50%. This equals 420 and 815 million tonnes of crude steel (World Steel Assosiation 2017). As China is a developing country, other industrialising countries and regions may experience a similar growth pattern in the future.

There are no shortages of resources. Both iron ore and coke that is used for primary production in the BF/BOF are easily available in several countries (U.S. Geological Survey & U.S. Department of the Interior 2017). The availability of secondary steel to be reprocessed in the EAF in the future, and where it will be available, is important. This knowledge can help decide where to invest and what technology, either BF/BOF or the EAF, should be build in the future. The BF/BOF is considered to have a higher emission-intensity than the EAF. This is because the scrap used in the EAF already has gone though the highly energy- and emissions-intensive reduction process from iron ore to pig iron. As the EAF-route utilised electricity, power production from renewable sourced could make the process nearly emissions free (Morfeldt et al. 2015). A presentation of the steel technologies can be found in Appendix A.1.

For the mean global temperature to not exceed 2.4°C above pre-industrial levels, the global emissions of CO_2 has to be reduced with 50-85% in the industrial sector by 2050. The projected global emissions reduction potential of the steel industry is set to 34% (Allwood et al. 2010).

2.1 Energy use in the steel industry

The production of goods from energy-intensive industries has increased as the world population and its wealth has grown (Worrell et al. 2009). The production of steel is a manufacturing process that uses a great deal of energy. To be able to fully implement the pledges made to lower greenhouse gas emissions, investments will have to be made towards energy efficient and low-carbon technologies in the energy sector. Up to 40% of the total investments into this sector between 2015 and 2030 will have to be used to reach the goals set (International Energy Agency 2015). If more renewable power generation technologies is used to produce electricity, there will be a significant reduction of the use of coal and gas in to the electricity industry. This will further lead to a reduction in emissions per unit output of electricity (Wiebe 2018).

If more renewable energy is used in the primary production of steel, the emission reduction potential for recycling the steel will go down (Gielen & Moriguchi 2002). To an effect, it means that the difference between the emissions from the two industries will lessen. This may reduce the incentive to recycle steel in the EAF and build EAF-plants. However, the total emission will go down as long as the steel is being recycled.

The amount of energy needed to produce molten steel differ due to the technology used, the quality of the fuel and what the furnace is charged with (scrap, DRI or iron ore)(OECD 2001). In the EU28 the energy intensity for the BOF is at 17-23 GJ/tonne crude steel. For the EAF it is 9.1-12.5 GJ/tonne steel when charged with scrap and 28.3-30.9 GJ/tonne when charged with DRI (Pardo et al. 2012).

An Life Cycle Inventory (LCI) study by Sandberg et al. (2001) for Sweden found the total primary energy consumption of steelmaking to be between 5958-8806 kWh/t for oxygen steelmaking, but for the EAF it can be as low as 1389-4250 kWh/t. The emissions of CO_2 in the EAF come from different sources both related to the steelmaking process and to the energy used. The emission are between 0.15-1.08 t CO_2/t for the EAF, while they are in the range of 1.61-2.60 t CO_2/t for the BOF (Sandberg et al. 2001).

2.2 Emissions from steel production[1]

The CO_2-emissions i the industrial sector mostly originate from the production of five different goods: steel, cement, plastic, paper and aluminium. 25 % of all carbon emissions from the industrial sector comes from steel production (Allwood et al. 2010). Steel is a non-renewable resource, so sustainable use, and re-use, is important.

The emissions from the steel industry vary widely from country to country and plant to plant. This is due to the fact that the emissions relies on the technology and energy used for that exact plant (OECD 2001). Emissions from steel production can be either be direct (fossil fuel combustion) or indirectly (electricity use and chemical reactions) (Milford et al. 2013). From the total emissions in 2006, 80% were direct emissions from the plants while 20% were indirect emissions from the electricity sector (Newman 2010).

In the BF the iron ore is reduced to pig iron, even though scrap metal and DRI can be used in some cases, and this process is almost solely based on the burning of fossil fuels. As this emits large amounts of CO_2, it follows that the steel industry does as well. Wanga et al. (2009) states that the BF emits approximately 70% of the total emissions from the BF/BOF and concludes that to minimise emissions from the BF, it should be charged with as much scrap as possible. However, this mix of charge is more costly than to use only iron ore to produce pig iron.

For the BF/BOF there are substantial secondary emissions as well. The coke and the sinter used in the BF are made in coke and sinter plants that are expensive and have large emissions to the environment during operation (Remus et al. 2013). In addition to this, there are large emissions from the mining of iron ores. Data from EXIOBASE, see Chapter 4.1, show that in some countries in 2014, including Germany, Japan and Romania, the CO_2-emissions from mining of iron ore were larger than from the BF/BOF per output.

The EAF emits less CO_2 because it is in most cases based on remelting scrap. However, it uses a good deal more electricity than the BF/BOF, and in many countries electricity production is highly emission intensive. Electricity use in the industry sector stands for 17% of the worlds total CO_2-emissions from fuel combustion and 66% of all electricity is produced from fossil fuels. Large steel producing countries such as China, India and Poland gets over two thirds of

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[1] This section is partly taken from Karlsen (2017)

their electricity from coal (International Energy Agency 2017).

The Open Hearth Furnace (OHF), the third steelmaking industry, uses more energy than the BOF, but has the advantage that it can be charged with scrap as well as pig iron (Worrell et al. 1999).The process in the EAF is quick and takes less than two hours while the capacity depends on the size of the mill. The BF/BOF can produce up to 350 tonnes in 40 minutes. The OHF is a lot slower than the BF/BOF or the EAF, and can take 10-12 hours to produce 600 tonnes (World Steel Association 2012).

As it is the EAF and the BF/BOF that dominate the steelmaking market, they will be compared to each other. Considering the direct emissions from the two technologies it is clear that the BF/BOF emits more CO_2 than the EAF. Both Newman (2010) and Hu et al. (2006) report numbers for CO_2-emissions per tonne crude steel from the BF/BOF to be around 2.2 and for the EAF they are between 0.5-0.7 t CO_2/t steel.

Milford et al. (2013) claim that most likely the steel technologies over time will converge to the standard of the best available technologies on the marked. This is due to high energy cost for the industry. This will effect the emission intensity of steel. In addition, development of future technology and energy emission intensities can effect the emissions from steel. As emissions from the EAF are lower than for the BF/BOF there will be an CO_2-emission reduction if there was a shift from BF/BOF to the EAF. This however, is dependent on scrap availability (Gielen & Moriguchi 2002).

2.3 Future of steel

As the world economy and population continues to increase, the production of steel will increase as well. However, the growth is suspected to be slower in the coming years due to the reduction of the domestic steel demand in China. In China there will be more focus on recycling and a circular economy, which will lead to less primary steelmaking (Pauliuk et al. 2011). Looking at the shares of BF/BOF, EAF and other technologies in Figure 2.2, there has been a decrease in the output share from the EAF and an increase from the BF/BOF since 1995. The share of EAF has gone down from approximately 34% in 2002 to 25.7% in 2016 (World Steel Association (2017) and World Steel Association (2003)). However, according to Basson (2015) share is predicted to go back up to 30% in 2019. Even though the share has gone down, the total output from the EAF has increased with 27% from 2002 to 2016 (World Steel Association (2017) and World Steel Association (2003)).

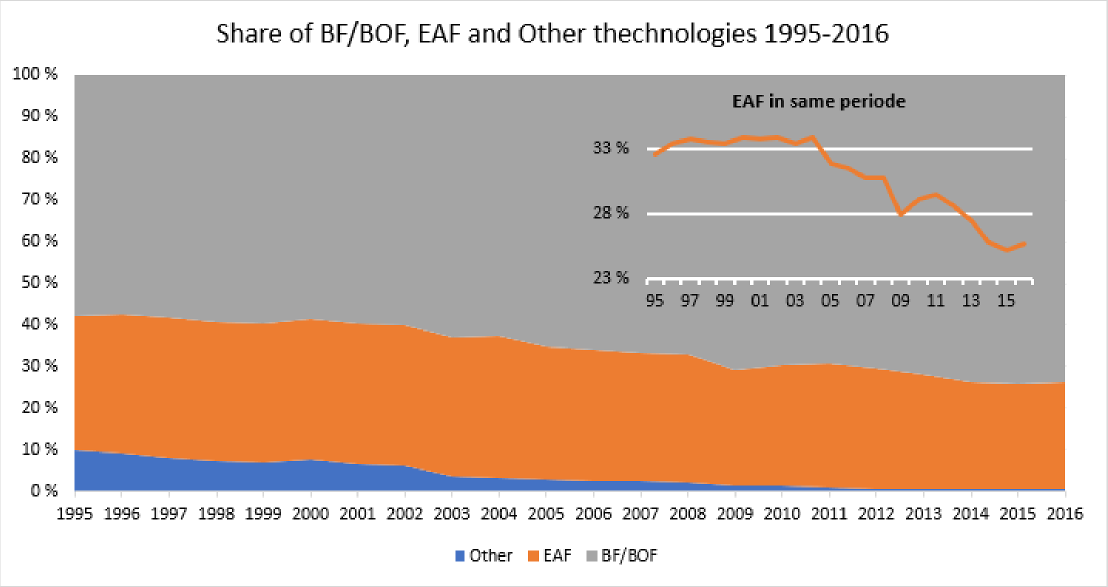

Figure 2.2: The share of BF/BOF, EAF and other technologies from 1995-2016 with a closer look at the EAF (World Steel Association (1996)-World Steel Association (2017)).

Milford et al. (2013) calculated the future emission for seven emission scenarios for steel. In their first scenario, "Business-As-Usual" (BAU), the emissions will peak in 2025 before subsequently decreasing and then increasing again. The decrease after 2025 is due to the increased use of the EAF, but the future demand for steel will then drag the emission back up. The predicted emissions for the "energy efficiency"-scenario are similar to the "BAU"-scenario, but the "energy and material efficiency"-scenario are lower. This is due to less primary steel production and more recycling and material efficiency (Milford et al. 2013). With more material efficiency and recycling the share of the BF/BOF will go down and the share of the EAF will increase leading to less emissions.

To determine the emissions from the steel sector in the future, the production of primary and secondary steel must be predicted (Milford et al. 2013). Hu et al. (2006) anticipates that it is the BF/BOF and EAF route, and not some novel technology, that will dominate in the future. However, there are ways of improving the current technology. In recent years the carbon intensity of steelmaking has gone down significantly due to several factors. Among these are the fact that the OHF has been replaced by the BF/BOF and the EAF. In addition in the BF/BOF the ratio between pig iron and steel has gone down, so the usage of the BF has been minimised. Continuous casting is now a common practice that is an energy saver for both the BF/BOF and the EAF (Hu et al. 2006). Together with continuous casting, to recovery gas from both the BF and the BOF and use it as fuel for the plant, is the best option (BAT) for reducing energy consumption in the BF/BOF (Remus et al. 2013).

Technologies under development have the potential of being more emission effective than current technologies. The use of Carbon Capture and Storage (CCS) during electricity production will indirectly lower the emissions from steel production, particularly from EAF. Another possibility is the use of Directly Reduced Iron (DRI) in the EAF. This is when iron ore is reduced in solid state instead of liquid state. This route can lead to only half the emissions of the BF/BOF-route. This is because gas replaces coal as a reducing agent in the BF before entering the EAF (Milford et al. 2013). This also leads to the EAF producing high quality primary steel and not secondary steel (Remus et al. 2013).

The European Ultra-Low CO_2 Steel making (ULCOS) initiative goal of 50% emission reduction by 2050 compared to the best practise today, can only be reached if the capacity of the EAF increases rapidly. According to Milford et al. (2013), this target can only be met by stopping the building of BFs before 2023. Morfeldt et al. (2015) believes that for this to be achievable, there will have to be incentives to adopt new and better technologies.

2.3.1 Scrap and secondary steel

Steel that is incorporated in products in the society, have a potential of being recycled in the future. The steel currently in use or integrated into products is called “in-use stock” or just “stock”. The consumption of steel today is a way of building up the current stock for the future (Pauliuk et al. 2013).

Steel is the most recycled material in the world. In a year more steel is being recycled than all other recyclable materials put together (World Steel Association 2009). Scrap metal is an important part of the production of new steel as the remelting of scrap is less energy consuming than the primary production. In addition, the recycling of steel will lessen the stress on landfills and there will be fewer products dumped in the environment. In the United Sates the biggest source of scrap was the recycling of automobiles with 14 million tones of steel in 2013 (U.S. Geological Survey & U.S. Department of the Interior 2017). However, secondary steel is not a perfect substitute for primary steel. This is due to the fact that the steel can not be cleanly separated from other contaminates during recycling (Milford et al. 2013).

Scrap can be divided into three different categories: home scrap, prompt scrap and End-Of-Life (EOL) scrap. The availability of home scrap, scrap recycled at the steel plant, have dropped after continuous casting was introduced and the yield loss was reduced. Prompt scrap comes from downstream processing industries. EOL scrap is often old and polluted with copper and other contaminants and therefore not always pure enough to be ideal for recycling. In some cases, for example in construction, it is better to reuse the already cast steel instead of remelting it, or cut it into smaller components. However, the effect of some pollutants can be lessened by mixing the molten scrap with pig iron or DRI while reprocessing (OECD 2013).

The availability of steel scrap in the future will depend on the consumption patterns today and the lifetime of the steel products. A large part of the produced steel will go into the building and infrastructure section. These sectors can have lifetimes of up to 75 years (Pauliuk et al. (2013) and Morfeldt et al. (2015)). From Karlsen (2017) the results showed that 31% of emissions from the steel industry in 2014 went into the construction sector and 16% into the production of machinery and equipment. In these sectors 85-90% of the steel was recycled in 2007 (World Steel Association 2009). Climate change mitigation, on the other hand, need to be managed withing the next few decades (Pauliuk et al. 2013). This means that the steel produced today will only lead to added emissions and not be recycled for decades. The difference that can be made at present will come from the current steel stock and that in the immediate future. Regardless of this unique quality of being 90% recyclable, the production share of primary steel, either BF/BOF or DRI-EAF, will have to be at least 50% in 2050, according to Morfeldt et al. (2015). This is due to the lag in the scrap availability.

To predict the available scrap in the future, the build up of the stock and the lifetime of the products must be determined (Pauliuk et al. 2013). The availability of scrap on the marked can be a contributing factor to the ratio of primary to secondary steel (Milford et al. 2013). Because of high consumption rates of steel in the later decades and due to the time lag between production and the recycling of the materials, there is a good chance of a higher scrap availability in the coming years (Gielen & Moriguchi 2002). The usable home scrap and prompt scrap is expected to decrease slightly due to improvements in yield losses. On the other side, the scrap recovery rate is expected to increase from 50-58% (Pardo et al. 2012).

However, Grosse (2010) concludes that recycling may not by itself reduce GHG-emissions and energy consumption, but mainly reduce the primary production. This way it can indirectly mitigate climate change and prevent resource depletion. If the growth rate of steel consumption continues and exceeds 3% increase a year, recycling of steel cannot stop depletion.

Material Flow Analysis (MFA) can be used to determine the scrap supply in the future, as products containing steel is traded between countries (Hatayama et al. 2010). MFA can be used to further developed and improve current ways of production, use and recycling, by better understanding the cycle of different materials (Yellishetty et al. 2010). Pauliuk et al. (2013) combined data on the consumption of steel per capita and forecasts of the world population to find this stock. They found that today most of the supply of scrap comes from the developed world. However, after 2025 China this will most likely be the biggest supplier, and towards the end of the century the developing world be be a largest supplier (Pauliuk et al. 2013).

2.4 What-if scenario analysis

To explore the future and alternatives that may happen, can provide powerful and important information to those individuals making decisions. Scenario analysis and sensitivity analysis can be used to accomplish this.

Scenario analysis is a tool that can be employed to find different variations of the future. It is not always what is most likely to happen in the future that is of interest. Sometimes seeing consequences of certain actions may be just as useful. The most effective way of creating a scenario analysis, is to have several, between two and five, alternative scenarios of the future that differ in outcome (Duinker & Greig 2007).

Sensitivity analysis is a tool that helps determine how much a model is dependent on its input data. By varying the input factors in a model while the remaining factors stay the same, the output data can be studied. The varying factors will have a different influence on the output (Saltelli et al. 1999). Sensitivity analysis can be utilised when there are uncertainties (Saltelli et al. 2000).

The analysis done in this paper can not be called either a scenario or a sensitivity analysis as it is less complex than these methods. It is therefore called a ”what-if“-analysis where only one input is changes at a time.

2.5 Technological change[2]

As Modaresi et al. (2014) states, a technological change can take several decades to come into effect. A lot of time can pass between an idea is made for a new technology, the technology is invented and the technology is fully implemented in the market(Silva & de Carvalho 2016). Considering the long lifetime of a steel plant and the high investment costs, the technological shift can be slow (Wanga et al. 2009). An example of this is the method used in the BOF where oxygen is injected into the pig iron. This was first thought of by Henry Bessemer in 1856, but the first top-blown pure-oxygen test was not done until almost a century later, in 1948 (Silva & de Carvalho 2016).

Most of the technological change nowadays has been incremental innovation that improved an already implemented technology. The result of this, is that the technology the modern steel plants consist of, is a product of knowledge and experience over decades (Silva & de Carvalho 2016). In addition to this, the investment cost of a technology will gradually shift the technology towards the cheaper alternative. The investment cost for a BF/BOF plant is in average twice that of the EAF leading to believe in a shift in this direction (Hidalgo et al. 2005). However, the

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[2] This section is partly taken from Karlsen (2017)

BF/BOF is often located on a plant that covers an area of several square kilometers containing coke oven plants, sinter plants and pelletisation plants, though all does not need to be situated at the same place (Remus et al. 2013).

In some countries technological change can be even harder due to a technological lock-in - Russia is an example of this. Russia would need a massive investment into their steel producing plants to replace their current and outdated technology, the OHF (Wiebe 2018).

A technological lock-in can happen if there is no incentive to replace the current technology. If the steelmaking route already in place has been there for a longer period, the unit production cost have decreased over time and the technology will have a "sunk cost" from earlier investments. If the technology is still yielding a benefit, the incentive to replace the outdated technology will not be there (Foxon 2007).

In these cases, to implement technologies that may improve the emissions-intensity of the plant can be an alternative. Examples of technologies that has improved the steelmaking already are Coke Dry Qenching (CDQ) and Top-Pressure recovery (TPR). CDQ is a technology that can recycle more than 80% of steam from the heated coke. This steam can then be used to produce power. TPR can recycle fuel for electricity production, up to 25-50 kWh per ton of steel (Hasanbeigi et al. 2011).

However, in the future these measures may not be sufficient as the emissions to the atmosphere has to be significantly lowered. As shift from the emission-intensive technologies and power sources towards more environmentally friendly solutions has to be made. Carbon Capture and Storage (CCS) has been pointed out to be one of the breakthrough technologies to achieve this in the steel sector for the future(Silva & de Carvalho 2016).

2.6 Carbon footprint calculation in input-output model[3]

Carbon Footprinting (CF) is defined as the direct and indirect GHG emissions, measured in tonnes of CO_2-equivalents with a time horizon of a 100 years (in Life-Cycle Assessment (LCA) called Global Warming Potential (GWP100)), that is emitted to meet the required final demand. So it is a consumption based concept (Minx et al. 2009).

There are several methods that are used to calculate the CF. Input-Output (IO) analysis can be used to find both the direct and the indirect emissions from a process with a specified final demand. Environmentally extended IO-analysis takes environmental pressure data for all industries in the model and links them together with other sectors. The pressures for these industries can then be found using the final demand, as shown in Chapter 3 (Minx et al. 2009).

LCA can be used to calculate the total emissions over the lifetime of a product. It compiles all

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[3] This section is taken from Karlsen (2017)

the environmental flows of a process through the entire lifetime: production phase, use phase and end-of-life phase(Hawkins et al. 2013). Then it takes the results and change them into environmental impacts. An example of this is the Intergovernmental Panel on Climate Change (IPCC) GWP100 where GHGs are presented in CO_2-equivalents which is almost identical to the CF (Hellweg & i Canals 2014). A full LCA of the BF/BOF and EAF in Poland was done by Dorota Burchart-Korol (2013).

The last method that is used for assessing environmental impacts is Material Flow Analysis (MFA). A product containing steel in the anthroposphere can cross national boundaries many times through trade which leads to emissions. MFA is then used to track these movements of the metals to get an overview of the situation and identify the environmental impacts of it (Liu & Muller 2013). Stock-driven MFA that contains product lifetime, population, and stock patterns can be used to forecast the use and need for steel in the major steel using industries. This data can then be utilised to estimate the carbon footprint of the stock of a material (Pauliuk et al. 2011).

"Input-output analysis of material flows with application to iron, steel and zinc" is an article by Konijn et al. (1997) that uses both MFA and IO analysis to discuss the environmental problems linked to materials and energy. In addition, Pauliuk et al. (2011) has a paper on "The Role of Stocks in the Chinese Steel Cycle".

In this analysis the IO-method is used with a Multi Regional IO-table (MRIO). This is because steel is a major input in several industries and products that are traded internationally. The inter-industry relations as well as bilateral trade are therefore important, and they are present in the MRIO database. Environmentally extended MRIO (EE-MRIO) is used to find the carbon footprints (Wieland & Giljum 2016). More information on this in the Methodology section in chapter 3.

Wieland & Giljum (2016) states that in 2011 the share of GHGs that were emitted from inside the EU was 62%. This means that more than one third of direct and indirect GHG emissions that are released due to European final demand, is emitted outside of the EU. This is a trend that has fallen from 80% since 1995. This can be found using the MRIO model.

To find the level of emissions in a base year with the estimated technology from a year in the future, say 2020, the final demand of the base year will be combined with the input structure and emission intensities of 2020. This will be done by altering the MRIO data. The emissions in 2020 with the technology from the base year can also be found. Wiebe (2018) states that CO_2-emissions will decrease in the electricity, mining and quarrying and coke and refined petroleum products industries when substituting 2020 technology (wind and PV) for the base year of 2010.

3. Methodology

3.1 Input-Output Table (IOT)[1]

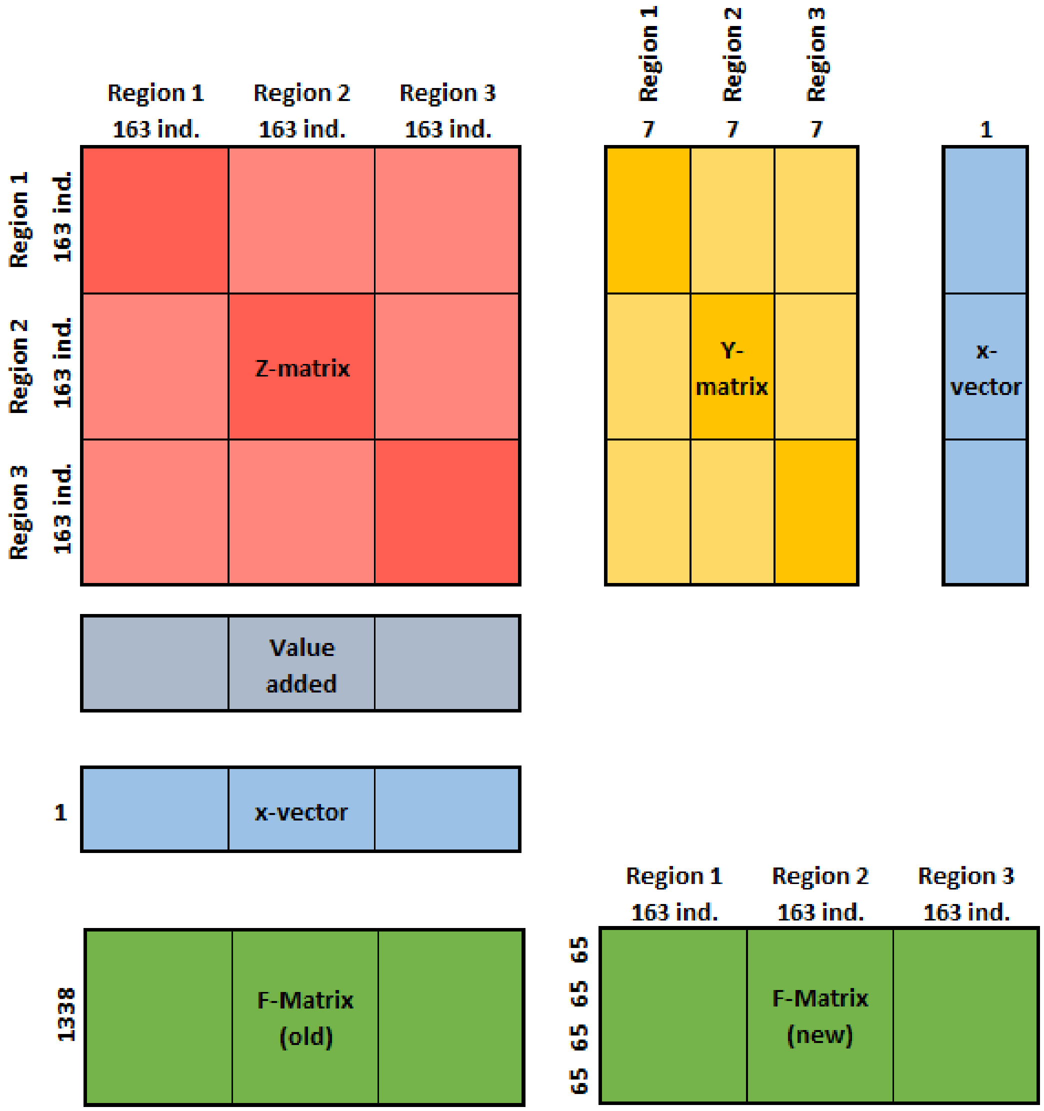

Figure 3.1: Multi-regional flow matrix (Z), Y-matrix, x-vector, value added matrix and the old and new F-matrices.

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[1] This section is taken from Karlsen (2017)

The Multi-Regional Environmentally Extended Input-Output Table (MR EE IOT) from EXIOBASE, see 4.1 consists of data from 49 regions with 163 industries each, as shown in Figure 3.1. A MRIO-Table shows the flows between industries both domestically and internationally. MRIO links economies together though bilateral trade, as mentioned in section 2.6. The data from EXIOBASE, see 4.1, is presented as industry-by-industry and in monetary terms.

The flow matrix (Z-matrix) contains the domestic IOTs for each country/region on the diagonal. On the off-diagonal presents the bilateral trade data between two countries/regions.

The Y-matrix is the final demand. On the diagonal is the final demand as a result of domestic demand. On the off-diagonal the final use of imported industries are located.

The x-vector is the total output of each countries/regions industries. It can be found by summing the rows of the flow matrix and the final demand matrix. The value added matrix can be used together with the Z-matrix to find the x-vector by summing over all the columns.

The F-matrix represents the environmental and labour extensions for each country/region and industry. There are two different stressor-matrices, one old and one new. The old stressor matrix contains 1338 different extensions, while the new has 4 categories (energy use, net energy use, emission relevant energy carriers and CO_2 combustion) with 65 extensions in each.

The intermediate co-efficient-matrix (A-matrix) has the same dimensions as the Z-matrix and shows the total inter-industry requirements. The A-matrix is calculated in EXIOBASE, but can be found from Equation (3.1). It is in the intermediate coefficient matrix the technology is represented in the IO-model (Wiebe 2018).

$$A = Z\hat{x}^{-1} \tag{3.1}$$

The S-matrix is the stressor matrix that shows the emissions from the F-matrix per output. The S-matrix is calculated in EXIOBASE, but can be found using Equation (3.2).

$$S = F\hat{x}^{-1} \tag{3.2}$$

The characterisation-matrix (C-matrix) contains 500 conversion factors in EXIOBASE. Among them is the Global Warming Potential (GWP100) conversion factor.

3.2 Supply-Use-Table (SUT)

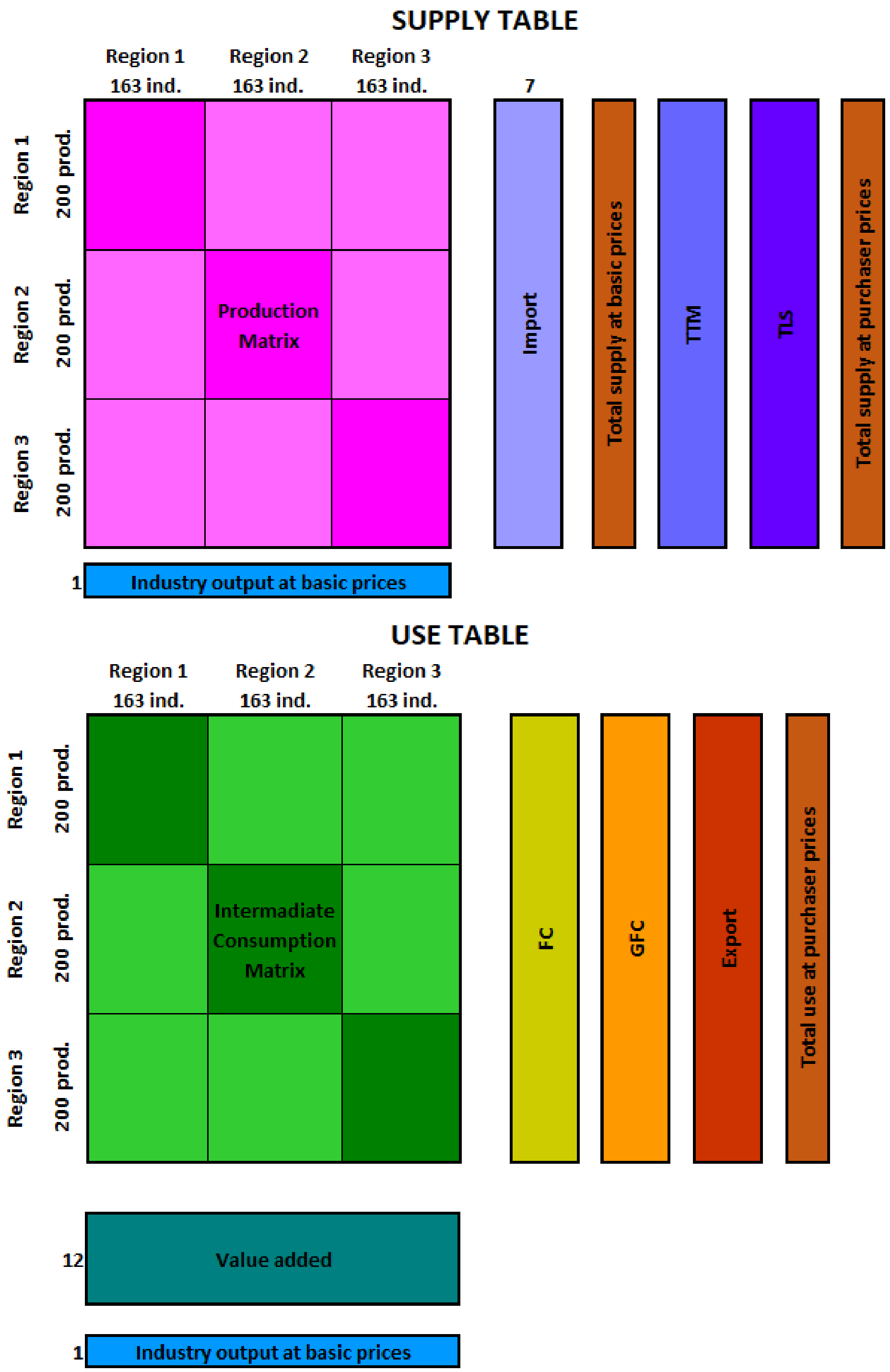

Figure 3.2: Multi-regional supply- and use-table (MRSUT).

The Multi-Regional Supply-Use-Table (MR EE IOT) from EXIOBASE consists of data from 49 regions with 200 products and 163 industries each, as shown in Figure 3.2. A MRSUT shows the use and supply of products that goes into and out from the different industries.

The production matrix in the Supply-Table has the dimensions of products x industries with products in the rows and industries in the columns. It shows the output of products from the industries. An industry can produce several products, not only the primary product. The primary product in the steel industry is steel, but there is also a substantial production of secondary products, like slag for the construction sector, electricity and transportation services. Also, the steel sector may not the only industries that produces steel. Several other industries may have steel as a secondary product.

In the MR supply-table, the off-diagonal matrices are all zero as a industry only supplies in the country of origin.

The columns in the intermediate Use-Table show the goods and services that are necessary to produce the products in a specific industry. Some products are necessary in almost all industries, like electricity, while other are specific for certain industries, like iron ore to the steel industries.

The Supply- and Use-Tables are connected so that the total use equals the total supply.

The Use-coefficient matrix:

The use-coefficient matrix can be used to relate the numbers in the use-table to each other. To calculate the use-coefficient matrix, the industry output must be found, see Figure 3.2. This is done by summing the columns of the intermediate matrix, with both imported and domestic products, together with the sum of the value added matrix. The use-coefficient matrix is found by dividing each row in the intermediate matrix, with imported and domestic products, with the industry output, as indicated in Equation (3.3). The resulting matrix will have the same dimensions as the intermediate matrix.

$$\text{Use coefficient}_{ij} = \frac{\text{Intermediate}_{ij}}{\text{Industry output}_{i}} \tag{3.3}$$

To find the use of products by the two steel industries, the corresponding columns are extracted and examined.

The market share matrix:

The market share matrix is a way to analyse the supply-table. The market share matrix is found by dividing each column of the supply-table by the total supply of industries. To find the total supply, see Figure 3.2, the columns of the product matrix is summed. The resulting matrix shows the share of the total supply of a product from a industry.

$$\text{Market share matrix}_{ij} = \frac{\text{Production}_{ij}}{\text{product output}_i} \tag{3.4}$$

3.3 Re-allocation of data in the use-table to change technologies

As the results from the project work, where the emission-intensity from the EAF were higher than from the BF/BOF, see section4.2.1, was not in correlation with the literature, the data had to be re-allocated according to the known facts. To change the technologies towards a more correct version, the use of these technologies must be re-estimated.

3.3.1 Re-estimating the use-table based on technology-specific information

When changing the technologies there are rules that has to be followed. When re-allocating the use of the products, the industry output of the new and re-allocated columns has to be equal to the old industry output. This means that if one unit is allocated from the BF/BOF to the EAF, one unit has to be re-allocated the other way as well.

To do the re-allocation in EXIOBASE, the individual use-tables for each country, with the domestic and imported use added together, was calculated. This forms a product x industry-table for each country as illustrated in the first matrix in Equation (3.5).

To do the re-allocation the ideal percentages of the different products for each industry was found using literature and previous knowledge. After all products were re-allocated using the percentages, see the second matrix in Equation (3.5), the industry output (excluding value added) where checked and compared to the original industry output (excluding value added), see Equation (3.6). If these did not match, some use had to be allocated back. This was done using specific "buffer-products" used in both industries. The total use (excluding final consumption, gross capital formation and export) of the two industries also needed to be equal to the original total use (excluding final consumption, gross capital formation and export), see Equation (3.7). This re-allocation method was done for each individual product and country separately.

$$\begin{vmatrix} use_a^{1k} & use_a^{1(k+1)} \\ use_a^{2k} & use_a^{2(k+1)} \\ use_a^{3k} & use_a^{3(k+1)} \\ use_a^{4k} & use_a^{4(k+1)} \\ use_a^{5k} & use_a^{5(k+1)} \\ \ldots & \ldots \\ use_a^{nk} & use_a^{n(k+1)} \end{vmatrix} \Rightarrow \begin{vmatrix} new\_use_a^{1k} & new\_use_a^{1(k+1)} \\ new\_use_a^{2k} & new\_use_a^{2(k+1)} \\ new\_use_a^{3k} & new\_use_a^{3(k+1)} \\ new\_use_a^{4k} & new\_use_a^{4(k+1)} \\ new\_use_a^{5k} & new\_use_a^{5(k+1)} \\ \ldots & \ldots \\ new\_use_a^{nk} & new\_use_a^{n(k+1)} \end{vmatrix} \tag{3.5}$$

$$x^k = \sum_{n=1}^{N} use^{nk} = \sum_{n=1}^{N} new\_use^{nk} \qquad \forall k \tag{3.6}$$

$$row^n = \sum_{k=1}^{K} use^{nk} = \sum_{k=1}^{K} new\_use^{nk} \qquad \forall n \tag{3.7}$$

use$_a^{nk}$, where n is the product, k is the industry and a is a country. x^k is the industry output (excluding value added) for industry k and row^n is the total use (excluding final consumption, gross capital formation and export).

The re-allocation of the use-table will lead to changes in the extensions matrix. The new values in the extension matrix will have the same adjustment in percentage as the corresponding products in the use-table. This was also done seperatly for each country.

3.3.2 Trade shares and new IOT

As the changes are made in the use-tables for each country, the values must be allocated to the correct places in the industry vector where the domestic and imported use is taken in to account. To do this a trade share vector is created. This shows how much of the total use of a product in a country is domestic or imported, and which country it is imported from. The calculations can be found in Appendix A.4.4 in section 5. The new use values can then be multiplied with the trade shares to find the new industry column that has the dimension (products·countries) x 1. The new industry vectors can now replace the old vectors in the MR use-table, and the MR use-table can be divided into two matrices, one for only domestic data and one for imported data. This matrices would be fed into the customary MatLab-script used at NTNU that generates the new industry by industry IOT, using the industry technology assumption. From now on, the data created using these calculation will be referred to as the ”current data after re-allocation“ as opposed to the ”old data before the re-allocation“.

3.4 Implementing a switch from BF/BOF to EAF

When changing the technology of an industry, the use-table is being altered. However, to change the shares of the technologies between two industries, the changes has to be implemented in the supply table.

In the supply-table the supply of a product from an industry is presented. Multiple industries can supply the same product, but one industry usually has one product as its primary product. This industry will have the majority of the total supply of this product and the highest market share. To change the technology share of a specific industry, the supply from that industry needs to be re-allocated to another industry.

$$\begin{vmatrix} sup_a^{1k} & sup_a^{1(k+1)} \\ sup_a^{2k} & sup_a^{2(k+1)} \\ sup_a^{3k} & sup_a^{3(k+1)} \\ sup_a^{4k} & sup_a^{4(k+1)} \\ sup_a^{5k} & sup_a^{5(k+1)} \\ ... & ... \\ sup_a^{nk} & sup_a^{n(k+1)} \end{vmatrix} \Rightarrow \begin{vmatrix} new\_sup_a^{1k} & new\_sup_a^{1(k+1)} \\ new\_sup_a^{2k} & new\_sup_a^{2(k+1)} \\ new\_sup_a^{3k} & new\_sup_a^{3(k+1)} \\ new\_sup_a^{4k} & new\_sup_a^{4(k+1)} \\ new\_sup_a^{5k} & new\_sup_a^{5(k+1)} \\ ... & ... \\ new\_sup_a^{nk} & new\_sup_a^{n(k+1)} \end{vmatrix} \tag{3.8}$$

sup_a^{nk}, where n is the product, k is the industry and a is a country.

The new supply values are found by multiplying constructed shares with the total supply of the chosen product. From the example in Equation (3.8) the calculations from the old supply-table to the new can be found in Equations (3.9)-(3.11).

$$tot\_sup_a^1 = sup_a^{1k} + sup_a^{1(k+1)} \tag{3.9}$$

$$new\_sup_a^{1k} = share^{nk} \cdot tot\_sup_a^1 \tag{3.10}$$

$$new\_sup_a^{1(k+1)} = share^{n(k+1)} \cdot tot\_sup_a^1 \tag{3.11}$$

$$share^{nk} + share^{n(k+1)} = 1 \tag{3.12}$$

The shares that are changed in the technologies due to the changes in the supply-table will be used in the what-if analysis.

3.5 Calculating consumption-based emissions[2]

To find the emissions embodied in final consumption, Equation (3.13) is used. This calculated the environmental footprint of the countries.

$$P = S(I - A)^{-1} y \tag{3.13}$$

Here P stands for Pollution, or emissions calculated, and I is the identity matrix. The I-matrix has the same dimensions as the A-matrix and consists of 1's on the diagonal and 0's at the off-diagonal. The final demand-matrix (y) in EXIOBASE consists of 7 different final demand categories (final consumption expenditure by households, final consumption expenditure by non-profit organisations serving households (NPISH), final consumption expenditure by government, gross fixed capital formation, changes in inventories, changes in valuables and exports: total (fob)) for each country as indicated in Figure 3.1. These were added together to have total final demand by country.

To find the CO_2-emission from the steel industries is the objective here. To find these emissions, the row in the S-matrix that represents the CO_2-emission is selected and diagonalized. The resulting P-matrix will show the CO_2-emissions related to production horizontally and consumption vertically. Equation (3.14) is a example of the results with three countries (a, b and c) and three industries (1, 2, and 3).

$$\begin{bmatrix} p^1_{aa} & p^1_{ab} & p^1_{ac} \\ p^2_{aa} & p^2_{ab} & p^2_{ac} \\ p^3_{aa} & p^3_{ab} & p^3_{ac} \\ p^1_{ba} & p^1_{bb} & p^1_{bc} \\ p^2_{ba} & p^2_{bb} & p^2_{bc} \\ p^3_{ba} & p^3_{bb} & p^3_{bc} \\ p^1_{ca} & p^1_{cb} & p^1_{cc} \\ p^2_{ca} & p^2_{cb} & p^2_{cc} \\ p^3_{ca} & p^3_{cb} & p^3_{cc} \end{bmatrix} = \begin{bmatrix} s^1_a & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & s^2_a & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & s^3_a & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & s^1_b & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & s^2_b & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & s^3_b & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & s^1_c & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & s^2_c & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & s^3_c \end{bmatrix} \cdot L \cdot \begin{bmatrix} y^1_{aa} & y^1_{ab} & y^1_{ac} \\ y^2_{aa} & y^2_{ab} & y^2_{ac} \\ y^3_{aa} & y^3_{ab} & y^3_{ac} \\ y^1_{ba} & y^1_{bb} & y^1_{bc} \\ y^2_{ba} & y^2_{bb} & y^2_{bc} \\ y^3_{ba} & y^3_{bb} & y^3_{bc} \\ y^1_{ca} & y^1_{cb} & y^1_{cc} \\ y^2_{ca} & y^2_{cb} & y^2_{cc} \\ y^3_{ca} & y^3_{cb} & y^3_{cc} \end{bmatrix} \tag{3.14}$$

p^k_{ij}, y^k_{ij} and s^k_i where k is the industry, i is the producing country and j is the consuming country. The L-matrix is Leontief inverse, $(I - A)^{-1}$, that shows the requirements of one industry to produce one unit of final demand from another industry. The Leontief inverse has the same

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[2] This section is taken from Karlsen (2017)

dimensions as the A-matrix.

To find the consumption based emissions from a specific industry for a specific country, the values corresponding to this industry in the column corresponding to the chosen country have to be summed. For example, if the goal is to find the consumption based emissions in country a from industry 2, the emissions will be:

$$p^2_{aa} + p^2_{ba} + p^2_{ca} \tag{3.15}$$

The total emission embodied in consumption is found by summing the entire column for each country. This can be used to find the share of consumption based emissions from steel and from other industries.

From the P-matrix in Equation (3.14) the emissions embodied in consumption from domestic production and from import can be found. The domestic emissions will be the the coefficients from the P-matrix when the subscripts are equal: p^k_{aa}, p^k_{bb} and p^k_{cc}. The imported emissions to a country will be in the same column as the domestic consumption. However, to find the emissions that only originate from steel, the S-matrix can be alterede like in Equation (3.16). The industry that the emissions come from is on the diagonal, while the rest is set to zero.

$$\begin{bmatrix} 0 & 0 & 0 \\ p^2_{aa} & p^2_{ab} & p^2_{ac} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ p^2_{ba} & p^2_{bb} & p^2_{bc} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ p^2_{ca} & p^2_{cb} & p^2_{cc} \\ 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & s^2_a & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & s^2_b & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & s^2_c & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \cdot L \cdot \begin{bmatrix} y^1_{aa} & y^1_{ab} & y^1_{ac} \\ y^2_{aa} & y^2_{ab} & y^2_{ac} \\ y^3_{aa} & y^3_{ab} & y^3_{ac} \\ y^1_{ba} & y^1_{bb} & y^1_{bc} \\ y^2_{ba} & y^2_{bb} & y^2_{bc} \\ y^3_{ba} & y^3_{bb} & y^3_{bc} \\ y^1_{ca} & y^1_{cb} & y^1_{cc} \\ y^2_{ca} & y^2_{cb} & y^2_{cc} \\ y^3_{ca} & y^3_{cb} & y^3_{cc} \end{bmatrix} \tag{3.16}$$

When summing the values in column number one in the P-matrix from Equation (3.16), the results will be the same as in the example in Equation (3.15). When we want to look at the production based emissions, on the other hand, the P-matrix can be summed horizontally.

When using the new extensions the same approach is used, but the difference in the structure of the extensions matrices has to be accounted for. For example, if the emissions from CO_2 from the new extensions shall be compared to the old extension, all the 65 stressors related to CO_2-combustion has to be summarised and inserted in Equation (3.13).

3.6 Calculating emissions embodied in downstream industries from steel[3]

When the emissions embodied in downstream industries from steel is going to be located, the S-matrix from Equation (3.16) is used, but the y-matrix has to be altered as well. Continuing with example from Equation (3.14), to find the emissions embodied in industry 1 as a result of production in industry 2, the resulting P-matrix will have the form as in Equation (3.17). The y-matrix in Equation (3.17) has been altered so only the final demand of the chosen industry 1 is present for all countries, all other industries are set to zero.

$$\begin{bmatrix} 0 & 0 & 0 \\ p^2_{aa} & p^2_{ab} & p^2_{ac} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ p^2_{ba} & p^2_{bb} & p^2_{bc} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ p^2_{ca} & p^2_{cb} & p^2_{cc} \\ 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & s^2_a & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & s^2_b & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & s^2_c & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \cdot L \cdot \begin{bmatrix} y^1_{aa} & y^1_{ab} & y^1_{ac} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ y^1_{ba} & y^1_{bb} & y^1_{bc} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ y^1_{ca} & y^1_{cb} & y^1_{cc} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{3.17}$$

To find the total share of emissions in industry 1 from the production in industry 2, the total emissions embodied in consumption in the downstream products has to be found, not only for industry 1, but for all three of them combined. This is accomplished by using the S-matrix from Equation (3.14) and the y-matrix from Equation (3.17). This then has to be done three times i three separate calculations, one for each industry. The share of emissions in industry 1 due to industry 2, is then the emissions from industry 2 divided by the summed total emissions from industry 1, 2 and 3.

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[3] This section is taken from Karlsen (2017)

4. Data

4.1 EXIOBASE [1]

EXIOBASE V3 with base year 1995-2014 is a global Multi-Regional Environmentally Extended Supply and Use/Input-Output Table (MR EE SUT/IOT) database. It contains data from 44 countries and five world regions that covers 95% of the global Gross Domestic Product (GDP). It was created by gathering SUTs from different countries and estimating the emissions and the resources of the 163 industries and 200 products. The MR EE IOT is developed from the EE SUT that has been converted to a MR EE SUT (Wood et al. (2014) and Tukker et al. (2013)). A representation of the MR EE IOT is shown in Figure 3.1. Here there are two different extensions. In this paper the new extensions from Schmidt et al. (2018) will mainly be used. The SUT is presented in Figure 3.2 in Chapter 3.

From EXIOBASE in the description of the industries the interpretation of the BF/BOF is represented in the class that has the description “Manufacture of basic iron and steel and of ferroalloys and first products thereof" and has the description code “i27.a". From the ISIC Rev.3 code (United Nation Statistics Division 2017) this industry or class includes among other the operation of the blast furnace, the production of primary metal products, of pig iron and steel ingots. The casting of the steel is not included. These are most of the operations that takes place in the BF/BOF from the charging of the BF and until before the casting of the molten steel.

The EAF is represented in the EXIOBASE as “Re-processing of secondary steel into new steel", “i.27.a.w".

4.2 Re-estimating the use-coefficients and emission and energy extension

4.2.1 Why this is necessary

The results from Karlsen (2017) show that the majority of the Greenhouse Gas-emission (GHG-emission) intensity in all EXIOBASE countries in 2014 where higher for the EAF than for the BF/BOF. This does not reflect the literature that say the BF/BOF has larger emissions than the

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[1] This section is taken from Karlsen (2017)

EAF. This data was based on the old extension-matrix. Because of this, there is a need to check this data in EXIOBASE to determine if there are errors in the data and where they are located.

In the following sections the use-table and the use-coefficient table is examined to analyse the use of products in the industries to see why re-allocations are needed to be made. In addition to this, the emission relevant energy carriers and the CO_2 emission data is investigated and the data from the old extensions is measured against comparable data in the new extension to further observe the need for changes to be made.

Use of products in the steel industry

From the use-coefficient matrix, see section 3.2, it is clear that different countries have very different product inputs into their steel industries. An example of this is that in China, 13% of the BF/BOF industry use comes from computer services and 29% can be related to trade. This data is supported by World Steel Assosiation (2011) that show China as the biggest exporter of steel world wide. In the US, 11% is related to trade, and the majority of the use (29%) comes from basic iron and steel. Between 0.5 and 0.8% of the total use for China and the US comes from iron ore for primary production.

For the EAF the dominating energy source is electricity from hydro power and nuclear for China and the US. In addition, the US has some input of electricity from coal. The largest product going into the EAF industry in China is called "Secondary raw materials" which is scrap metal. In the US in 2011 there was 5% input of "Secondary raw materials" to the BF/BOF and only 0.2% into the EAF. Even though the BF can be charged with some scrap, most should be used in the EAF. Only seven of the EXIOBASE country had more input of scrap metal in to the EAF than to the BF/BOF.

Overall, there is a higher use of electricity per output in the EAF than in the BF/BOF. The only exception is the use in 2000 by EU28 where the electricity use is higher for the BF/BOF than the EAF. This data is though corrected in 2007, 2011 and 2014. The data for the EAF for the EU28 countries seems to be higher per output for several products into the EAF then it should. These are also adjusted for in the later data sets.

An interesting fact when analysing the electricity use data, is that India has almost no input of any electricity to the steel technologies in all the data from 2000, 2007, 2011 and 2014. However, they have a higher usage per output of various types of coal and coke, and the usage has increased from 2000 to 2014. This is due to the fact that India makes steel from DRI which does not require electricity but coal or natural gas. Apart from India the allocation of electricity should mainly be allocated to the EAF and also the share of electricity should be considerably higher for the EAF than for the BF/BOF.

Emission relevant energy carrier

The emission relevant energy carriers from the stressor (extension) matrix in EXIOBASE shows the emissions relevant to the production of steel. The emission relevant energy carriers differ from country to country. Table 4.1 shows the old (used in the master project) and new data for two emission relevant energy carriers: Blast Furnace gas and Other bituminous coal. The emissions related to these energy carriers have for some of the countries been drastically changed from the old to the new extensions. These adjustments can have a big effect on the emission from the steel industry.

The data concerning the BF-gas show that for the majority, almost 90%, of the countries, the BF-gas per output is higher for the EAF than for the BF/BOF. When looking at the total for the energy carrier, 70% of the countries has a higher total for the EAF than for the BF/BOF. The EAF producing steel from scrap will not need any input of BF-gas, however, countries using DRI to charge their EAFs will need a BF for the reducing process of the iron ore and there may be some emissions related to this.

For "Other bituminous coal" the emissions in Russia has gone from 17 to 66 658 TJ in the BF/BOF and from 6 to 25 729 TJ for the EAF.

Table 4.1: The total emission relevant energy use in the old and new extensions for the top steel producers in 2014. Calculations can be found in A.4.2.

	Blast Furnace gas					**Other Bituminous Coal**			
Country	**Old extension**		**New extension**		**Country**	**Old extension**		**New extension**	
	BF/BOF	EAF	BF/BOF	EAF		BF/BOF	EAF	BF/BOF	EAF
China	2 680 344	197 929	1 907 949	225 081	China	1 957 538	17 518	2 302 505	15 115
Russia	91 956	151 504	74 168	97 653	India	1 017 370	61 565	1 633 338	184 650
Japan	90 532	24 056	132 704	36 223	Brazil	63 971	1 763	75 306	3 043
India	76 708	126 883	106 445	197 584	Japan	63 096	6 548	37 378	31 852
Germany	30 761	42 819	33 955	37 321	Germany	26 610	758	3 733	768
United States	28 188	32 018	24 340	25 787	United States	16 278	-	7 309	-
Brazil	14 598	14 096	2 775	11 563	EU28	2 970	119	1 814	433
South Korea	5 557	1 804	1 882	406	Russia	17	6	66 658	25 729
EU28	2 453	3 432	2 226	2 965	South Korea	-	-	-	-

For EAF, the emissions from natural gas are significantly higher in the new extensions for all but seven EXIOBASE countries. On the other hand, emissions from natural gas use in BF/BOF are significantly lower in United States, Japan, China, South Korea and Brazil and 25 other countries.

CO_2-combustion data

The CO_2 combustion data for the old extensions are taken directly from the S-matrix, this data can be found in Figure 4.1. This shows the CO_2-emissions per output from combustion for all EXIOBASE countries. In 2014 about 60% of the countries had CO_2-combustion-emissions that were lower for the EAF than for the BF/BOF.

In the new extension-matrix there are 65 extensions that are related to the CO_2 combustion data. This data shows the emissions related to the use of products in the use-table. It is assumed that the old data from the stressor matrix can be compared to the sum of all the CO_2 combustion data from the new extension, this is done in Figure 4.1. For the selected countries/region seven out of the nine presented countries have higher emissions in the new extensions than in the old.

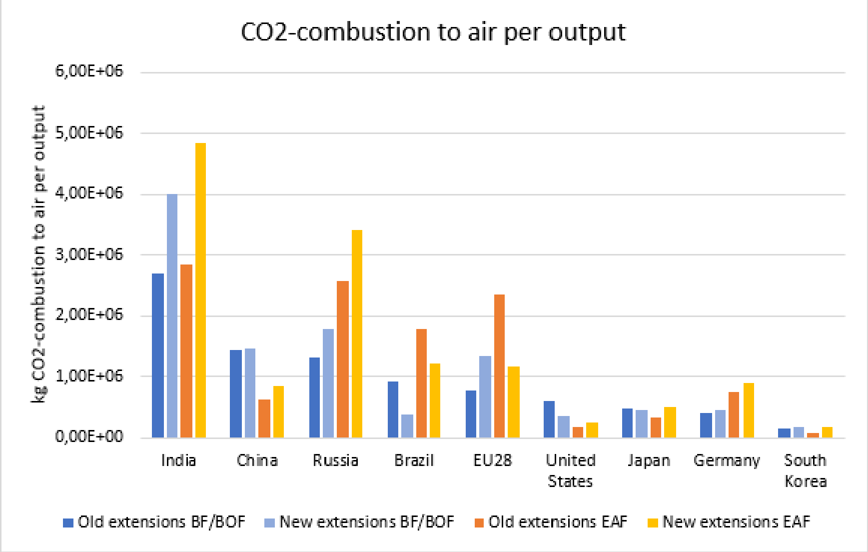


Figure 4.1: The emission of CO_2 to air for selected countries with old and new extensions. Data from EXIOBASE. Calculations in Appendix A.4.5 in section 4.4.

This data does not reflect the literature where the EAF should have less emissions due to the use of electricity as opposed to coal-based products. In the use-table, however there are use of products in the EAF that should not be there. Examples of this are the use of “Blast Furnace Gas” in countries that does not use DRI and “Coke oven gas”. In Germany 70% of the CO_2-emissions from the EAF came from BF-gas. Germany does have some production of primary steel from the EAF using DRI. However, the emissions from the BF-gas is higher for the EAF than for the BF/BOF when it should be significantly lower. An explanation for the high use of these gases can be that electricity, gas and water supply is reported as one and thus allocated between the industries in the same shares. For Germany, the electricity, gas and water supply have the same input-share in the two steel industries. For the data to be correct, the data must be re-allocated and allocated correctly between the industries.

4.2.2 How the re-estimation is done

From the analysis of the data made in this sections above, it is clear that the data in the use-table as well as in the extensions are not in line with the literature. In light of this, re-allocations has to be made as described in section .

Because of this incorrect usage of some products in the steel industries, re-allocations where made in the use-table according to Table A.1 in Appendix A.2. As changes where made in the use-table and the use-coefficient-table, the extensions related to the re-allocated product also changed at the same rate.

4.2.3 Comparisons

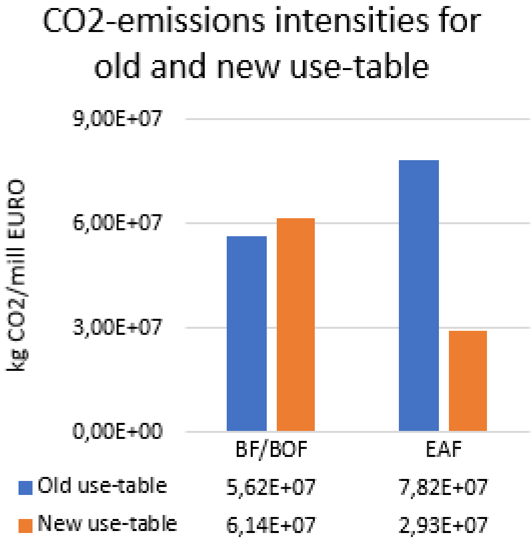
CO_2-emission intensities

Table 4.2 show the CO_2-emission intensities related to the old data with the old extensions (before re-allocation), the old data with the new extensions and the current data after the re-allocations with the new extension for both the BF/BOF and the EAF. The change from the new extensions to the modified extensions is due to the changes in the use-table. As Table 4.2 shows, the CO_2-emissions intensities vary from country to country and for the two different steelmaking routes.

The CO_2-emission intensities in the old extension for the two technologies show that the majority, 26 of the 45 countries, have a higher emission intensity for the BF/BOF than for the EAF. For the new extension, this share has gone down some, to 23 countries out of the 45. However, this does not reflect the real world. The emission intensities might be higher for the EAF due to the fact that in EXIOBASE the output is presented in monetary terms and not physical terms. The unit in the extensions, or stressor, matrices is thus in kg CO_2 per million € (in Table 4.2 converted to tonnes CO_2 per million €). As the price of secondary steel is less than for primary, this may force the emission further up for a smaller unit of million € than it would for a higher unit (Cooper et al. (2016) and Mathiesen & Moestad (2004)). But, this does not fully explain how this comes about.

After the re-allocation, the emission intensity in EAF is higher than in BF/BOF for only six countries. Figure 4.2 show, there is a shift from the EAF to the BF/BOF. Now, BF/BOF is correctly classified as the more emission intense technology. The total emissions per output for all EXIOBASE countries has gone down with 33%. As the same extension as for the current date after the re-allocation is used in all the three what-if scenarios, see section 4.4, the CO_2-emission-intensities will not change.

The high emissions in India are due to the usage of coal-based DRI in the EAF. Mexico is the fourth highest producer of DRI, as Figure 4.7 shows. Nevertheless, the emission intensity for the country is lower for the EAF than for the BF/BOF, and considerably lower than for India. This is due to the fact that the DRI production in Mexico is based on natural gas and not coal. Natural gas has a relatively low CO_2-emissions compared to the coal-based DRI (Kim & Worrell 2002).



	BF/BOF	EAF
🟦 Old use-table	5,62E+07	7,82E+07
🟧 New use-table	6,14E+07	2,93E+07

Figure 4.2: The total CO_2-emissions intensities for all EXIOBASE countries from the steel industries for the old data and the current data after re-allocation in kg CO_2 per million €. Calculated in Appendix A.4.5 in section 4.5.

Table 4.2: The CO_2-emission intensities in tonnes CO_2 per million € for the old and the new extensions as well as the new extension after the re-allocation of the use-table. The red numbers indicate the highest value for that country and extension. The data for the Netherlands and Bulgaria are data errors. Calculations in Appendix A.4.5 in section 4.4.

	Old extension		**New extension**		**Re-allocated extension**	
	BF/BOF	**EAF**	**BF/BOF**	**EAF**	**BF/BOF**	**EAF**
Bulgaria	4 114	944	15 247	886	15 247	886
Netherlands	3 728	48 657	3 783	12 798	3 214	12 155
Slovakia	3 683	2 089	3 414	7 239	1 641	1 850
India	2 688	2 837	4 007	4 859	4 007	4 859
South Africa	2 226	906	1 088	1 429	1 525	139
Czech Republic	1 924	3 732	1 369	2 528	1 909	438
Luxembourg	1 450	233	6 489	110	6 489	110
China	1 444	620	1 468	853	1 503	513
Russia	1 318	2 582	1 773	3 413	2 185	1 477
Romania	1 211	954	1 148	1 622	2 093	375
Mexico	1 121	368	563	562	944	12
Brazil	918	1 783	381	1 225	525	217
Average EU28	775	2 343	1 341	1 165	1 411	653
Canada	619	775	577	1 333	1 194	7
United States	604	174	351	240	473	120
Turkey	596	327	326	295	571	19
Hungary	544	1 140	433	1 032	867	47
Poland	534	952	823	1 195	1 658	149
Norway	534	143	840	575	1 166	5
Indonesia	524	147	586	26	527	11
Japan	478	329	458	484	522	268
Sweden	442	454	377	468	519	91
France	442	577	349	552	598	7
Australia	429	1 140	248	184	263	117
United Kingdom	420	474	432	379	494	137
Slovenia	419	61	668	114	754	95
Germany	401	732	456	880	667	286
Belgium	390	309	378	375	478	96
Austria	374	667	466	1 102	533	680
Finland	358	345	362	427	348	467
Italy	310	151	469	323	750	5
Spain	257	208	339	299	752	138
Switzerland	183	234	363	131	295	109
Latvia	140	2 786	1	120	1	120
Lithuania	138	-	99	-	99	-
South Korea	138	75	174	172	192	44
Taiwan	135	182	134	136	179	26
Greece	120	16	210	59	165	47
Portugal	107	49	96	61	97	61
Denmark	80	-	54	-	54	-
Croatia	76	70	45	52	54	33
Ireland	26	-	27	-	27	-
Estonia	3	-	2	-	2	-
Malta	1	-	-	-	-	-
Cyprus	-	-	0	-	0	-

Energy carrier input

From the A-matrix the energy carriers for the steel industry can be found to determine which of the industries that uses most of the resources.

Table 4.3: Average energy carriers for all EXIOBASE countries in 2014 from the before and after the re-allocation of the use-coefficient table. Data from EXIOBASE before and after re-allocations. Calculations can be found in Appendix A.4.5 in section 3.

	Before re-allocation			**After re-allocation**		
Industry	**BF/BOF**	**EAF**	**Diff.**	**BF/BOF**	**EAF**	**Diff.**
Mining of coal and lignite; extraction of peat	1,43E-02	1,20E-02	2,45E-03	1,48E-02	1,09E-02	3,84E-03
Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	6,12E-04	6,12E-04	0,00E+00	5,20E-04	4,92E-04	2,79E-05
Extraction of natural gas and services related to natural gas extraction, excluding surveying	6,12E-04	4,08E-04	2,04E-04	5,46E-04	4,36E-04	1,10E-04
Extraction, liquefaction, and regasification of other petroleum and gaseous materials	2,04E-04	0,00E+00	2,04E-04	1,99E-04	1,02E-05	1,89E-04
Mining of iron ores	6,06E-02	4,08E-04	6,04E-02	6,03E-02	2,00E-04	6,01E-02
Manufacture of coke oven products	1,02E-02	4,29E-03	5,71E-03	1,22E-02	3,45E-04	1,18E-02
Manufacture of cement, lime and plaster	6,12E-04	4,08E-04	2,04E-04	6,60E-04	3,72E-04	2,88E-04
Recycling of waste and scrap	3,55E-02	2,82E-02	7,35E-03	3,09E-02	3,19E-02	-1,55E-03
Production of electricity by coal	2,04E-03	6,12E-03	-4,16E-03	2,31E-03	6,49E-03	-4,18E-03

Table 4.3 shows that all but one of the energy carriers presented are larger for the BF/BOF than for the EAF for the old data before the re-allocation. The ”Production of electricity by coal“ is the only category that is dominated by the EAF. The mining of iron ores in to the BF/BOF industry is clearly larger for the BF/BOF than for the EAF.

For the current data after the re-allocation, the values have change for some of the energy carriers. The input per unit output of ”Mining of coal and lignite; extraction of peat“ and ”Manufacture of coke oven products“ has increased for the BF/BOF. The ”Mining of iron ores“ is still greater for the BF/BOF even though the difference has become smaller. The most noticeable change is that ”Recycling of waste and scrap“ now is larger for EAF. These changes show that the errors in the old data and the changes made there, improved the energy carrier input for the technologies towards the better in the new data after the re-allocation.

Even though the average for all the EXIOBASE countries are overall correct with regards to literature, for the majority of the countries some of the energy carrier data where incorrect.

4.3 Future of steel

Hatayama et al. (2010) uses dynamic material flow analysis to predict the steel stock from the base year 2005 to 2050. Their results show a steel use in 2050 that is six times the consumption in 2005 at 55 billion tonnes. The biggest part of the consumption is in Asia, and the stock is used in the building sector.

4.3.1 Recycling

Data from Pauliuk & Hasan (2017) show the flows between the processes in the steel production chain, which is illustrated in Figure A.1 in Appendix A.1. Data on the flow of steel from waste management to the scrap stock is represented in Figure 4.3. This graph shows a trend that more and more steel is being recycled from the waste management industry per kilo tonne steel used in production. There is, however, a decline from 2005. A can be seen from Figure A.1 and 2.1 the production of steel has been increasing, and is expected to increase. As scrap metal originate from steel waste, the availability of scrap today will have nothing to do with the consumption of steel today. This will be linked to steel produced decades ago as there is a delay due to the long lifetime of steel. However, as output of steel has increased, that stock has increased as well.

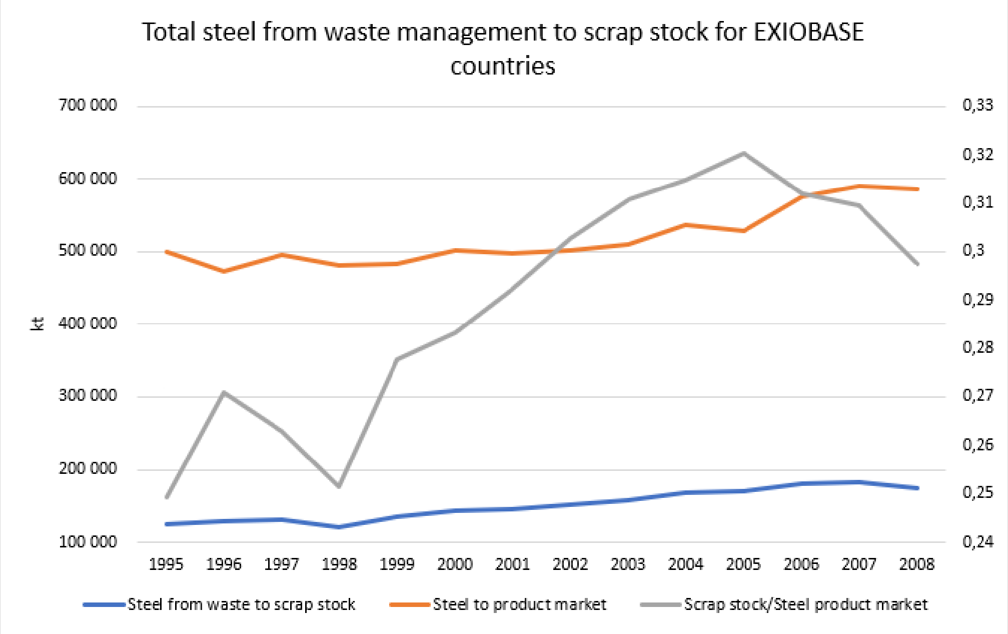


Figure 4.3: Graph of the trend of production and recycling in kilo tonnes from waste management to the scrap stock from 1995-2008 on primary vertical axis, and the ratio of recycling per production on secondary vertical axis (Pauliuk & Hasan 2017).

4.3.2 Country specifics

There are many parameters to consider when determining the shares of the two technologies in the future: the future population, Gross Domestic Product (GDP), demand, consumption, energy consumption and taxes on emissions. The in-use stock, the age of the current technology and plants as well as technological lock-ins must also be considered among others.

If the energy source becomes more renewable, the potential for reducing emissions through recycling will lessen (Gielen & Moriguchi 2002).

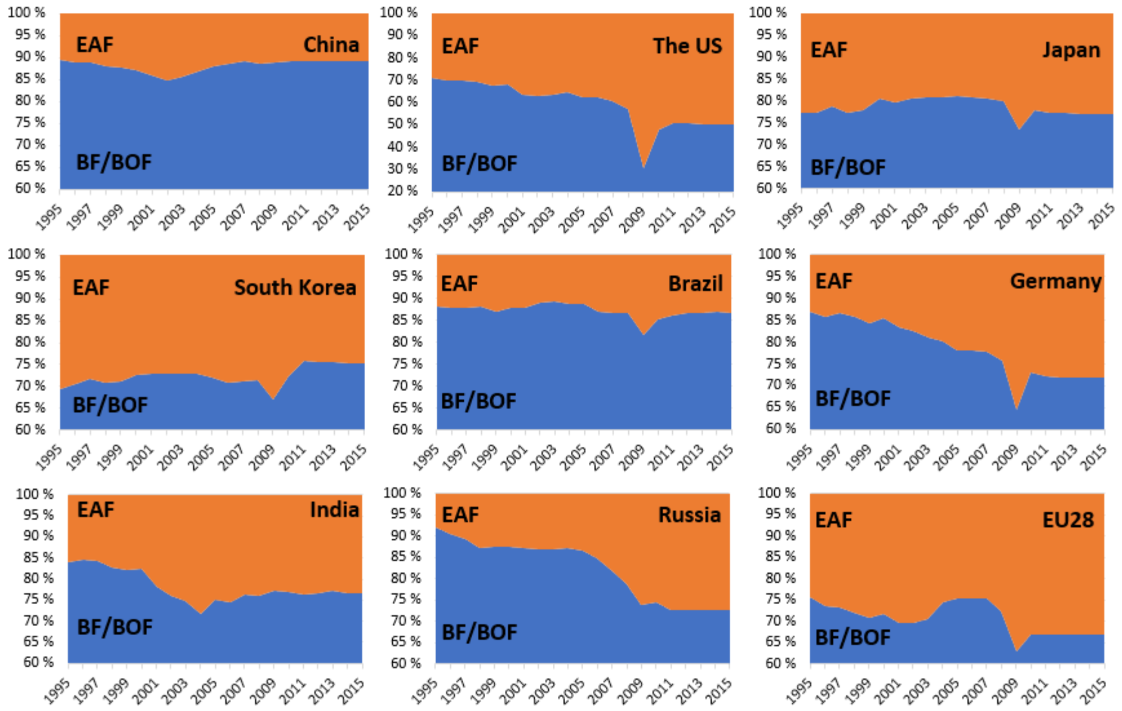


Figure 4.4: Historical overview of the shares of BF/BOF and EAF for the major steel producing countries. Note: all vertical axes goes from 60-100% except for the US. Data for EU28 is the overall average including Germany. Data collected from EXIOBASE. Calculations can be found in Appendix A.4.1.

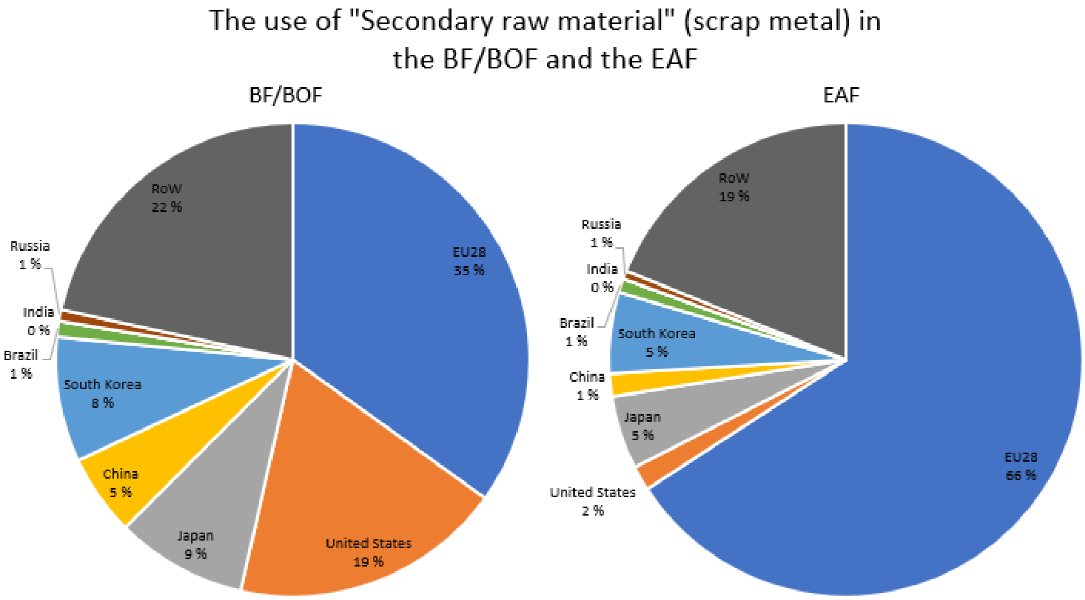


Figure 4.5: The use of ”Secondary raw material“ (scrap metal) in the BF/BOF and the EAF for the selected countries. Germany stands for 22% and 8% of the use in EU28. Data collected from the old EXIOBASE data.

China

China is the biggest steel producing country with almost 50% of total world production in 2016 (World Steel Association 2017). Approximately 94% of the Chinese steel production was done in the BF/BOF. This has not changed in later years according to World Steel Association (2017). However, the demand is expected to peak in 2025 and then decrease slowly (Yin & Chen 2013). The immense production is a result of a rapid growth in demand domestically as the population goes through an economic transition.

Despite being the largest producer, China is one of the major steel producing countries with the lowest energy efficiency. However, there have been improvements in the industry. OHFs and old BFs have been replaced with more modern BFs. From 2005 to 2007 the number of BFs in China increased from 46 to 63 (Guo & Fu 2010). Investments into these improvements must be expensive, and could lead to a technological lock-in, see Section 2.5. In this case the technology is newly implemented and to replace a second time is not cost effective.

The low share of steel production by the EAF, can be a result of low scrap availability as the steel production and consumption in China started to grow in the 1990s (Yin & Chen 2013). Therefore, the in-use stock in China would not be available for some decades. Figure 4.5 show that of the total scrap metal used in the world, China only stands for 5% of it in the BF/BOF and 1% in the EAF. This is in spite of China being the biggest steel producer by far. A high domestic demand for steel, see Figure 5.4, and no scrap would lead to production using the BF/BOF route. This can be seen in Figure 4.4 where the curve for China is fairly stable at around 90% for the entire time period. Figure 4.6 show that the import of steel to China has decreased in later years and is fairly low compared to other steel producing countries.

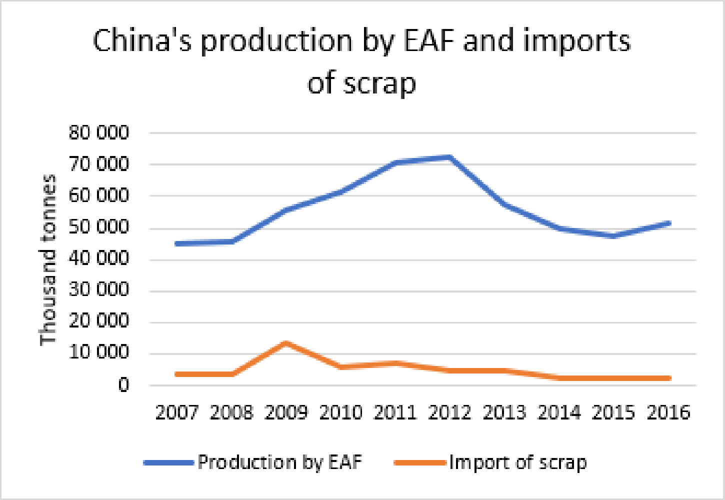


Figure 4.6: The production of steel from the EAF and the import of scrap in China in thousand tonnes crude steel and scrap metal (World Steel Association 2017).

When looking at the future for the Chinese steel industry they have issued the ”Circular Economy Law” (Pauliuk et al. 2011). For this to be implemented a substantial amount of EAFs must be build in China. The steel stock in China is growing due to the demand that started in the 1990s, and is expected to peak between 2025 and 2050 (Pauliuk et al. 2011). According to Wang et al. (2007) in an ambitious energy conservation plan for China, the share of the EAF will increase to 27% in 2020 and 33% in 2030.

EU28

The iron and steel industry in the EU is the second largest producer of steel in the world and it is responsible for 6% of the total CO_2-emissions in EU (Newman 2010). The consumption in EU is expected to continue to grow linearly, but in 2030 it will still be 8% lower than in 2007 due to the steel collapse in 2009 that can be observed in Figure 4.4 (Pardo et al. 2012). In 2006 (then EU27) Germany was the biggest producer of steel from the BF/BOF while Italy had the highest production of EAF-steel (Remus et al. 2013). Figure 4.5 show that the EU28 countries are by far the largest region to use scrap in the EAF at 66%, and 35% of the total scrap in the BF/BOF industry is used in one of the EU28 countries. EU28 is also the biggest total user of scrap metal.

As there will be a higher demand for steel, the demand for scrap will increase as well. This will lead to an increase in the share of EAF-steel to approximately 47% in 2030 (Pardo et al. 2012).

Japan

In 2014 according to EXIOBASE the share of EAF-steel was at 23% of the total Japanese steel output. Japan is the third largest producer of steel and the iron and steel industry account for 15% of Japan's total GHG-emissions (Newman 2010). Results from Hirato et al. (2009) shows that the steel stock in Japan has been increasing steadily from 1970 to 2005. Historically the share of EAF in Japan has been consistent, but Japan, as several of the other countries, had a reduction in the share in 2009. An increase in scrap availability will lead to a higher share of steel from the EAF. In 2025 the share of steel from EAF is predicted to be approximately 50% according to Gielen & Moriguchi (2002).

India

The fourth largest steel produces according to World Steel Association, is India, and data from EXIOBASE show that the BF/BOF is the main technology for steel production at 77%. However, this data differs from World Steel Association (2017) that says 57% of the steel is produced in the EAF. Of the total GHG-emissions from India, 8% is allocated to the iron and steel industry (Newman 2010). The remaining is from the EAF. However, as Figure 4.7 show, India produced DRI and charges their EAFs with this coal-based DRI that has a higher energy intensity than when charged with scrap metal. As EXIOBASE is based on prices, the low share can be attributed to a higher price for the steel produced in the EAF in India, as steel made from DRI is primary steel and not secondary as EAF-steel from scrap. The low usage of scrap metal can also be seen in the extremely low share of scrap metal used in the two steel industries in Figure 4.5. Change in the shares of the different technologies is assumed to be the same as the rest of the EXIOBASE countries.

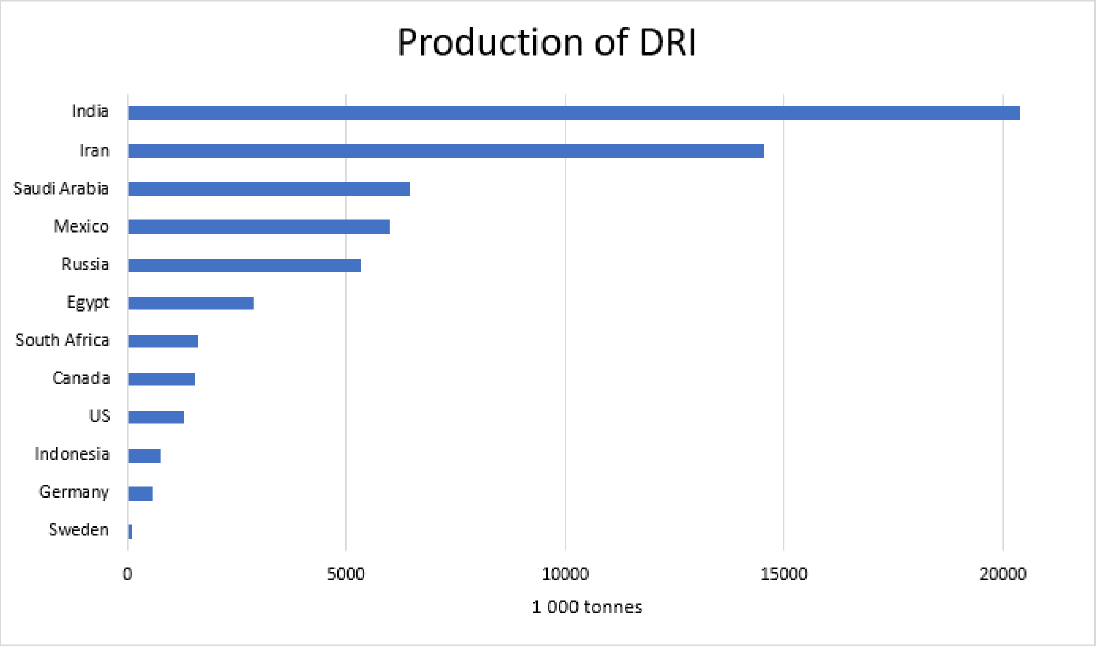


Figure 4.7: Data from World Steel Association showing the production of DRI.

The United States

Of the countries and regions presented here, the United States has the highest share of EAFs with 67% in 2016 (World Steel Association 2017). This is despite the fact that the usage of scrap in the EAF is only 4% of the total scrap usage in the world. Data from World Steel Association show that the United States is the largest importer of DRI in the world, at 33% (World Steel Association 2016). In the United States a total of 8% of the emitted GHG-gases came from the iron and steel industry in 2009 (Newman 2010). Change in the shares of the different technologies is assumed to be the same as the rest of the EXIOBASE countries.

Russia

11 % of the GHG-emissions in Russia originated in the iron and steel industry in 2009 (Newman 2010). Russia, together with Ukraine, are one of the two only countries that still use the OHF to produce steel with 2.4% of the production. The majority of steel comes from the BF/BOF with 66.9% (World Steel Association 2017). In 2013 many OHFs had been replaces with new EAFs or BOFs and, according to Ivanova (2013), the target for the share of OHF-production was set to 0% in 2015. This did not happen as the share was at 2.4 % at that time (World Steel Association 2017). However the share has fallen from almost 10% in 2010 (World Steel Association 2011).

In 2015 the steel production in Russia fell with 8.4% due to an economic recession. However the decline is not as steep in 2017 as earlier and the steel demand is expected to recover (de Carvalho 2017). Change in the shares of the different technologies is assumed to be the same as the rest of the EXIOBASE countries.

South Korea

South Korea did not start their steel production until 1970, but is now the seventh largest steel producer and 13% of the total GHG-emission are accounted for by the iron and steel industry (Newman (2010) and Lee & Ki (2017)). About 70% of the Korean steel is produced using the BF/BOF route (World Steel Association 2017).

Their share of EAF has increased slightly over the years, and they are the second larges country in total use of scrap in their EAF mills after EU28. Change in the shares of the different technologies is assumed to be the same as the rest of the EXIOBASE countries.

4.4 What-if scenario analysis: Data

For the what-if scenario analysis, the shares of the two different industries will be changed. There are two different scenarios: scenario 1 will change the shares to the most realistic future shares; and in scenario 2 the best available technology will be implemented. The new realistic steel technology shares and the shares for the best available technology are listen in Table 4.4.

To find the new realistic technology shares for BF/BOF and EAF literature was used, see 4.3.2. For EU28 the realistic average for all the countries are set to 53% for BF/BOF and 47% for the EAF. In EXIOBASE the change for the individual 28 countries had to be found so the overall realistic average was met. This was done by finding the old average of the shares (at 64.8% for BF/BOF and 35.2% for EAF) and calculating the difference to the new realistic average share. This tells us the change for each individual country. However, some countries had shares of EAF closer to a 100% than the average said they had to increase. These countries were set to a 100% and the increase for the remaining countries increased accordingly.

The new total average for scenario 1: realistic shares is 51% for the BF/BOF, which is acceptable as Morfeldt et al. (2015) concluded that there has to be at least 50% production of primary steel.

For scenario 2: BAT it is the EAF that is considered the best available technology. The share of the EAF is set to 75% of the total supply from the EAF industry. However, as Table 4.4 shows, the countries with share for the EAF higher than 75% will not be adjusted.

Table 4.4: The new realistic shares for the BF/BOF and the EAF for all EXIOBASE countries for the old data, scenario 1:realistic and scenario 2: BAT.

Country	**Old shares (2014)**		**New adjusted shares**		**BAT**	
	BOF	EAF	BOF	EAF	BOF	EAF
Austria	86 %	14 %	71 %	29 %	25 %	75 %
Belgium	60 %	40 %	45 %	55 %	25 %	75 %
Bulgaria	5 %	95 %	0 %	100 %	5 %	95 %
Cyprus	100 %	0 %	85 %	15 %	25 %	75 %
Czech Republic	79 %	21 %	65 %	35 %	25 %	75 %
Germany	72 %	28 %	57 %	43 %	25 %	75 %
Denmark	100 %	0 %	85 %	15 %	25 %	75 %
Estonia	100 %	0 %	85 %	15 %	25 %	75 %
Spain	27 %	73 %	12 %	88 %	25 %	75 %
Finland	79 %	21 %	64 %	36 %	25 %	75 %
France	69 %	31 %	54 %	46 %	25 %	75 %
Greece	21 %	79 %	6 %	94 %	21 %	79 %
Croatia	70 %	30 %	56 %	44 %	25 %	75 %
Hungary	69 %	31 %	55 %	45 %	25 %	75 %
Ireland	100 %	0 %	85 %	15 %	25 %	75 %
Italy	47 %	53 %	32 %	68 %	25 %	75 %
Lithuania	100 %	0 %	85 %	15 %	25 %	75 %
Luxembourg	1 %	99 %	0 %	100 %	1 %	99 %
Latvia	99 %	1 %	85 %	15 %	25 %	75 %
Malta	100 %	0 %	85 %	15 %	25 %	75 %
Netherlands	92 %	8 %	77 %	23 %	25 %	75 %
Poland	55 %	45 %	41 %	59 %	25 %	75 %
Portugal	41 %	59 %	26 %	74 %	25 %	75 %
Romania	57 %	43 %	42 %	58 %	25 %	75 %
Sweden	73 %	27 %	58 %	42 %	25 %	75 %
Slovenia	12 %	88 %	0 %	100 %	12 %	88 %
Slovakia	82 %	18 %	68 %	32 %	25 %	75 %
United Kingdom	71 %	29 %	56 %	44 %	25 %	75 %
United States	50 %	50 %	37 %	63 %	25 %	75 %
Japan	77 %	23 %	50 %	50 %	25 %	75 %
China	89 %	11 %	67 %	33 %	25 %	75 %
Canada	68 %	32 %	68 %	32 %	25 %	75 %
South Korea	75 %	25 %	62 %	38 %	25 %	75 %
Brazil	87 %	13 %	74 %	26 %	25 %	75 %
India	77 %	23 %	63 %	37 %	25 %	75 %
Mexico	58 %	42 %	58 %	42 %	25 %	75 %
Russia	73 %	27 %	59 %	41 %	25 %	75 %
Australia	80 %	20 %	66 %	34 %	25 %	75 %
Switzerland	24 %	76 %	11 %	89 %	24 %	76 %
Turkey	53 %	47 %	40 %	60 %	25 %	75 %
Taiwan	71 %	29 %	57 %	43 %	25 %	75 %
Norway	64 %	36 %	50 %	50 %	25 %	75 %
Indonesia	18 %	82 %	4 %	96 %	18 %	82 %
South Africa	73 %	27 %	59 %	41 %	25 %	75 %

5. Results and Discussion

5.1 Emission embodied in final consumption

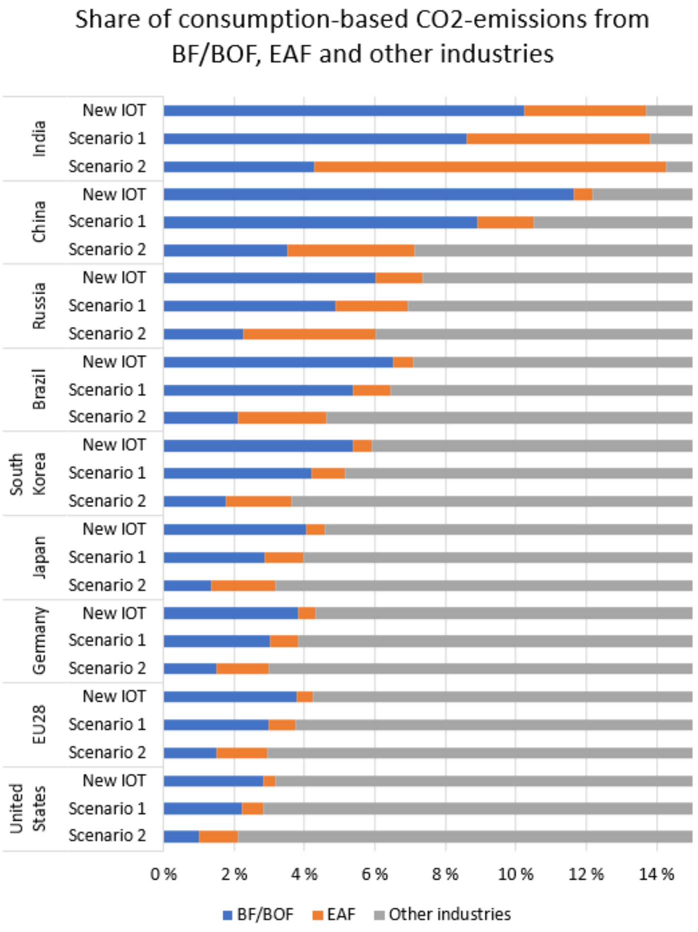


Figure 5.1: The share of total consumption-based CO_2-emissions from the steel industries and the remaining 161 industries in 2014 for the current data (NEW IOT) and the two scenarios. Data is collected from EXIOBASE after re-allocation of the use-table. Calculation can be found in A.4.5 under section 5.1-5-6.

The share of consumption-based CO_2-emissions allocated to the steel industries and to the remaining 161 industries for the current data after re-allocation and the two scenarios are presented in Figure 5.1. These results show that consumption-based CO_2-emissions embodied in steel from the different countries vary. For all the countries presented, the share of emissions allocated to the BF/BOF route is higher than the EAF route for the current data and for scenario 1: realistic. However, for scenario 2: BAT the share of emissions from the EAF is higher for all countries, except the EU28 region where it is slightly lower. As the BF/BOF stands for 65% of the output in the current data, it is reasonable that the majority of the emissions from steel should be allocated to this industry in the current data. Subsequently as the share of the EAF increases in the two scenarios, to 49% and 77%, the share of the emissions from the EAF increases as well.

The highest total share of emissions from steel in the current data is in India with almost 14%. In addition, India has the highest share of emissions from the EAF at 3.5%. China has the highest emission share from the BF/BOF at almost 12%.

The total share of emissions from the steel industries decrease from the current data to scenario 1: realistic and even more to scenario 2:BAT in all countries except in India. Here the share increases from 13.7% in the current to 13.8% and 14.3% in the two scenarios. These emissions were found using Equation (3.14) from Section 3.5, with data from the re-allocated use-table and the new extension-matrix.

Figure 5.2 presents the same data as in 5.1, however, the graph shows the total CO_2-emissions from the steel industries as opposed to the shares. In both Figure 5.1 and 5.2 the change due to the re-allocation made in the supply-table can be observed. It is clear that China is the country with the highest CO_2-emissions from the steel industries with India as the second largest.

Similar to the shares of the emissions, the total CO_2-emissions from the two industries decrease from the current data to the two scenarios for all countries except India. This decrease, however, is a consequence of a reduction of the emissions from the BF/BOF that is larger than the increase in the emissions from the EAF. This is the effect of the lower CO_2-emission-intensities for the EAF compared to the BF/BOF, see Table 4.2. For India, on the other hand, the emissions-intensity for the EAF is decidedly higher than the other countries (excluding the Netherlands) and it is higher than for the BF/BOF. This means that a shift from the BF/BOF to the EAF for India, as well as the Netherlands, Slovakia, Austria, Finland and Latvia, will lead to higher CO_2-emissions. As mentioned, the high emission-intensity of India is due to the fact that they charge their EAF with coal-based DRI.

Even though the emissions from the EAF have increased, in total the consumption-based CO_2-emissions from the steel industry has decreased from $1.96 \cdot 10^6$ Gt in the current data to $1.74 \cdot 10^6$ Gt i scenario 1: realistic and to $1.32 \cdot 10^6$ Gt in scenario 3. As steel is present in many products and industries, both directly and indirectly, a shift from the BF/BOF to the EAF will lead to less consummation-based emissions. Even though food does not directly contain steel, equipment and machines (tractors, trucks, electrical machinery etc.) that help process the food, contain steel. A shift in the industries from BF/BOF to EAF will then not only effect the emissions from the two industries themselves, but a large quantity of the other industries as well.

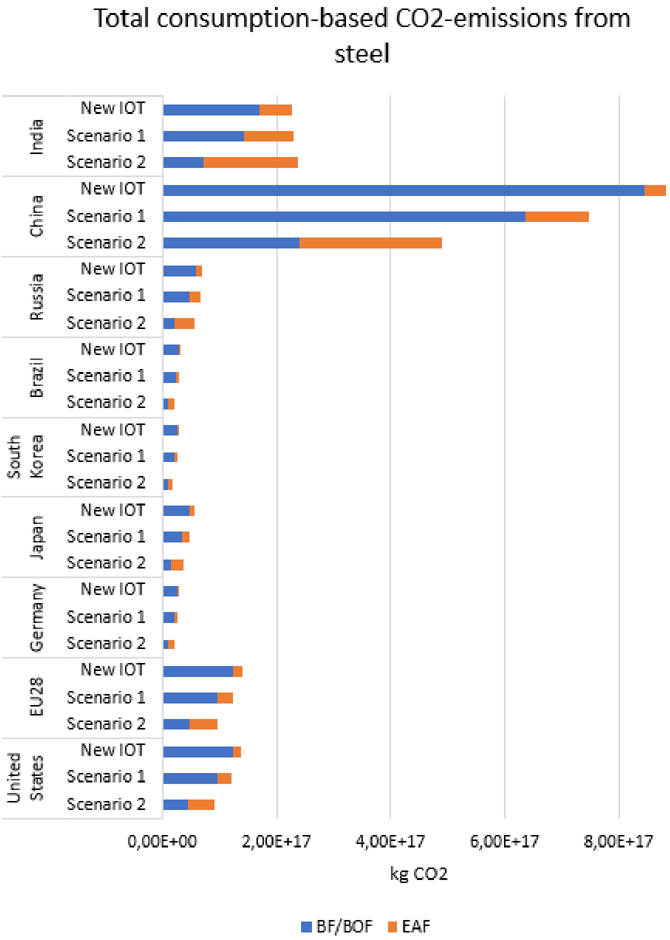


Figure 5.2: The total consumption-based CO_2-emissions from the steel industries for the current data and the two scenarios. Values in kg CO_2. Data from EXIOBASE in 2014 after reallocation. Calculation can be found in A.4.5 under section 5.1-5-6.

5.1.1 Emission embodied in final consumption per capita

When the CO_2-emissions embodied in consumption from due to final demand from Figure 5.2 is presented per capita, as in Figure 5.3, the results are more comparable. Data on the world population in 2014 from Table A.2 is used to find the normalised results in Figure 5.3. With the normalised results, it becomes clear that when considering the population of the countries, the impact changes. Even though India has the second largest total consumption-based CO_2-emissions, it is second to last of the represented countries when its large population is taken into account.

Of the EXIOBASE countries Luxembourg and Norway is the two countries with the highest consumption-based steel emissions in the current data and in the two scenarios. China is the third highest in the current data, while in the two scenarios Australia takes third place.

Both Luxembourg and Norway have high GDPs and a small population. Clearly it is the countries with high GDP's per capita that consumes most of the CO_2-emissions. According to the UN, European countries have high GDPs. China, on the other hand, has a very large population and the second lowest GDP per capita among the countries in this sample, only India has a smaller GDP (United Nations 2016). China had in 2014 a population of 1.397 billion people according to the United Nations (2017). Still the emissions per capita for China is the highest of the countries presented for the current data and scenario 1: realistic, while Russia and South Korea have higher emissions for scenario 3: BAT. This can be explained bu Russia and South Korea originally having higher shares of EAF than China.

The high emissions per capita for China is an indication of the immense production of steel in China and the emissions resulting from it. The high steel-consumption is a result of a large part of the population coming out of poverty. Jennings (2018) claim that almost 13 million people were lifted out of poverty in 2017.

The results of Luxembourg should be interpreted with some scepticism. In 2014, close to 164 000 people working in Luxembourg resided in neighbouring countries. That was approximately 30% of the population in Luxembourg at that time (United Nations (2017) and Luxembourg Times (2015)). This frontier working force can contribute to driving the consumption-based emissions in Luxembourg up and consequently marginally down in the France, Germany, the Netherlands and Belgium. However, as Luxembourg is a part of the EU28 countries, the results should balance out, as all the neighbouring countries also is a part of the EU.

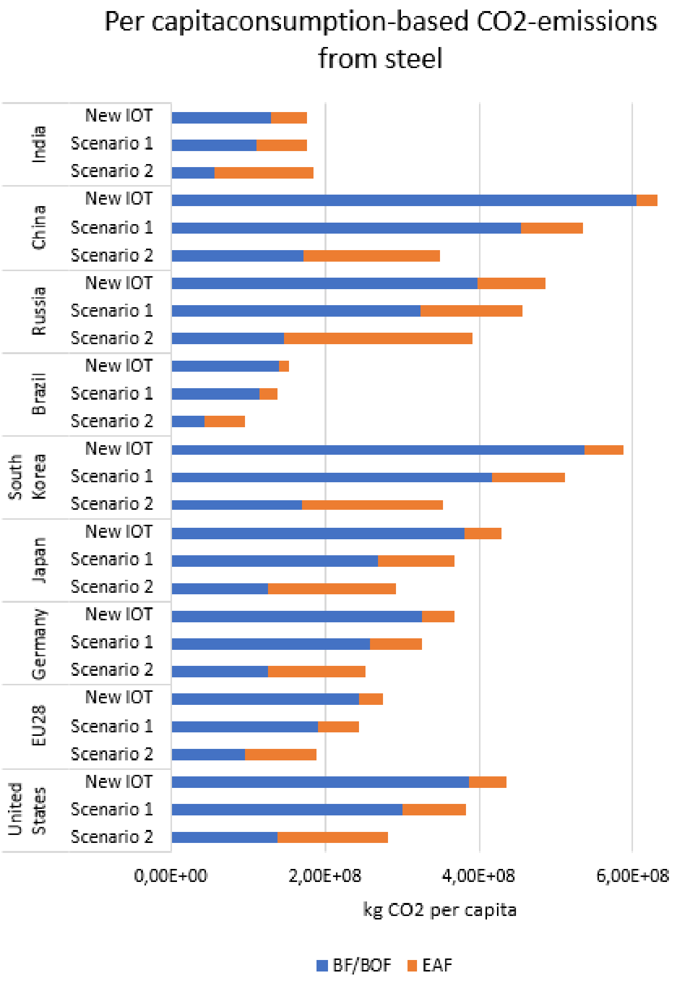


Figure 5.3: The consumption-based CO_2-emissions from the steel industries per capita in 2014 for the old and the new use table. Data is collected from EXIOBASE. Calculation can be found in A.4.5 under section 5.1-5-6.

5.1.2 Emission from domestic use and from import

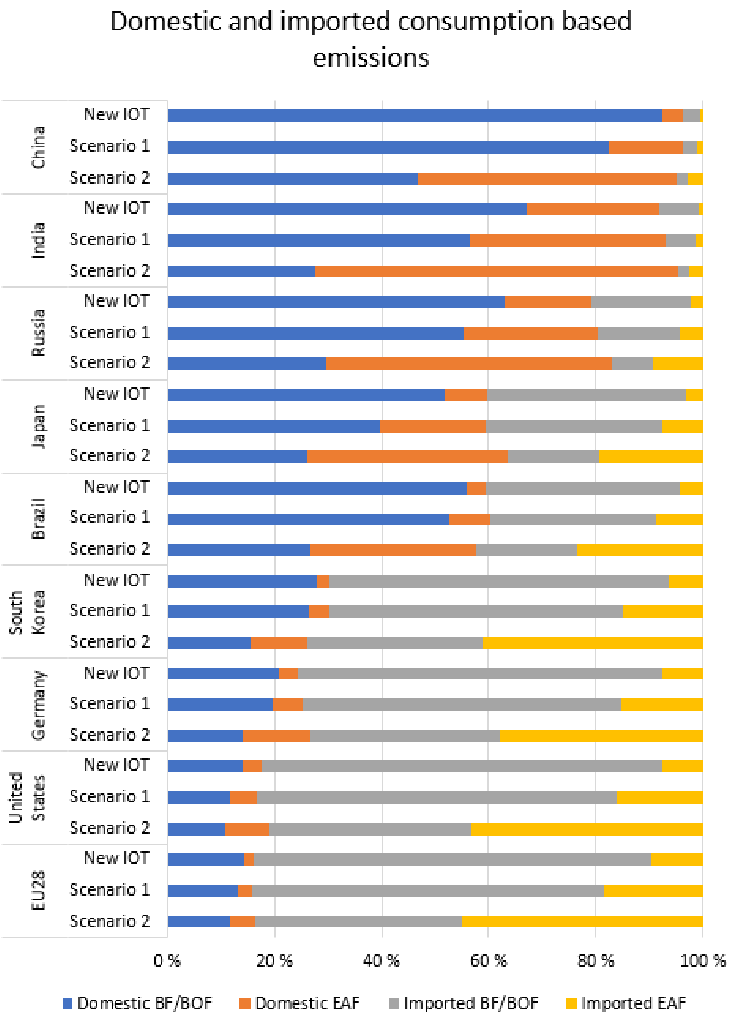


Figure 5.4: The shares of consumption-based CO_2-emissions from the steel industry that is consumed domestically and imported from other countries. Data from EXIOBASE for the current (New IOT) and the two scenarios in 2014 after re-allocation. Germany is included in the data from EU28. Calculation can be found in A.4.5 under section 5.8.

The consumption-based CO_2-emissions from the steel industries can be divided into the share that is consumed domestically and the share that is imported. This is done in Figure 5.4. The data is also divided between the BF/BOF and the EAF. The system set-up in Equation (3.16) was used to find these emissions with data from after the re-allocation.

The results from Figure 5.4 give the origin of the consumption-based CO_2-emissions from the two steelmaking technologies in Figure 5.2. As the results from these two figures (Figure 5.4

and 5.2) can be seen in relation to each other, it becomes clear that as the emissions from the EAF increase in Figure 5.2, the share in Figure 5.4, as well as Figure 5.1, increases. What Figure 5.2 and 5.1 do not show, is whether these emissions originate from the country itself or if it is imported.

For the presented countries, only South Korea, Germany, United States and EU28 have more of their CO_2-emissions imported than is consumed domestically. Only one country, South Africa, besides the countries presented in Figure 5.4, have more than 50% of the emissions consumed domestically. South Africa consumes 80% of its steel emissions within its boarders in the current data. The countries with the majority of emissions consumed within the country stands for 72% of the total output of steel after the re-allocation, where China represents 45%, according to EXIOBASE. This means that the production of steel and steel products in these counties can sustain its own population. In comparison all EU28 countries stand for only 10% of the total output, with Germany accounting for 3% of this.

Only one country, Malta, has no domestic consumption-based emissions and have a 100% imported emissions. In addition to Malta, five countries (Cyprus, Estonia, Ireland, Lithuania and Denmark) have no domestic emissions related to final consumption from the EAF route. There are no countries from Figure 5.4 that produce steel solely from the BF/BOF route. This applies to all the scenarios.

The total share from the EAF increases in Figure 5.4 due to the changes in the supply-table. In scenario 2: BAT the imported share for the EAF is larger than for the BF/BOF for all presented countries. The largest increase in percentage is for the United States where the share goes from 8% to 43%.

When the share of the EAF increases the total emissions increases as well. However, as Figure 5.4 shows for scenario 2: BAT, in countries with low emission-intensities from Table 4.2, it is the imported emission that increase most. The opposite is evident for the countries with high emissions-intensities. Even though the share of imported emissions to India from the EAF-route increase, the domestic emission share increases more.

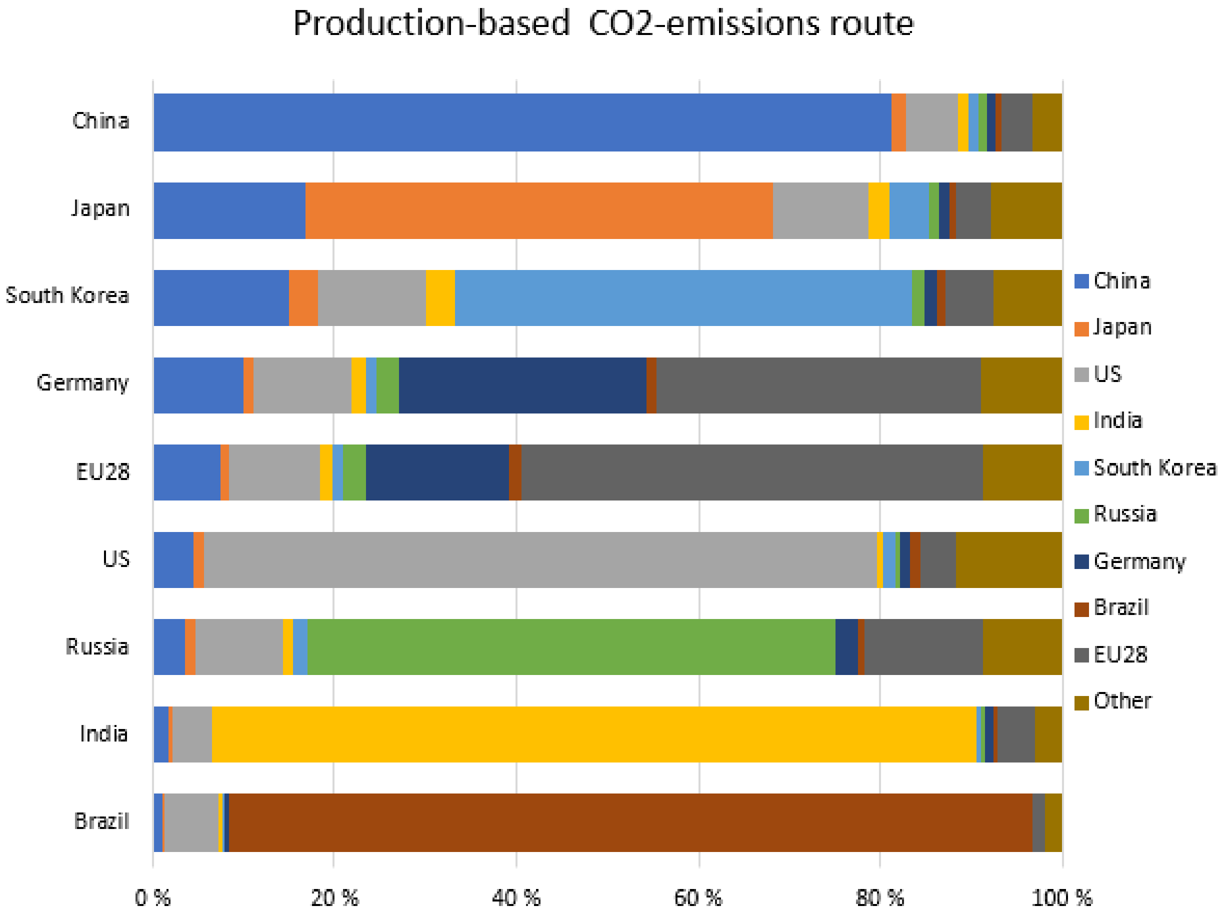


Figure 5.5: The share of the production-based CO_2-emissions and where it is exported to or if it is used domestically. Germany is excluded from the EU28 data to not double count these emissions. The new use-table and extensions are used after re.-allocation. Calculation can be found in A.4.5 under section 5.9.

The total amount of consumption-based CO_2-emissions from steel in a country may not equal the total amount of production-based CO_2-emissions. The domestic consumption and production-based emissions are though equal. Germany is a large producer of vehicles and exports with the vehicles the emissions related to the steel used in the product. Where the excess emissions are exported to is presented in Figure 5.5. All countries presented in Figure 5.5 except Germany have the larges part of the production-based emissions staying inside its boarder.

Even though 81% of the emissions in China is not exported, the total exported production-based emissions from China are significantly larger, with a minimum of one magnitude of order above the rest of the countries.

The results from Figure 5.4 and 5.5 show that the CO_2-emission-intensity for one country does not only effect the emissions inside that country. The flow of steel and steel products cross boarders in large quantities. This means a shift in one country can effect the consumption-based CO_2-emission world wide. However, the exports in Figure 5.5 may change in the future due to the tariffs the US has implemented on steel. There may be less export from the taxed countries (China, EU28, Canada, Mexico etc) to the United States and more imported from the countries that are not taxed (Australia, Argentina and Brazil) (Tuv et al. 2018).

To illustrate the fact that changes in one country can have a great effect on the consumption-based CO_2-emissions, the total emissions was found for the current scenario with only the share of the EAF in China changed to that of scenario 2: BAT. This was also done for India, now with the share in China set back to the current data. As Figure 5.6 shows, by only changing the share of EAF in China, the total consumption-based CO_2-emissions will become lower than for the realistic scenario. However, doing the same for India leads to a higher total CO_2-emissions than for the current data. This demonstrates the consequence that the different countries have on the total picture.

As climate mitigation requires lower CO_2-emissions, a shift towards steel produced from scrap will help. However, for the countries with higher emission-intensity for the EAF-route, the opposite is more effective. But as the world will always need new primary steel, this is not a major problem. In addition, these countries would benefit from improving their current EAF technology.

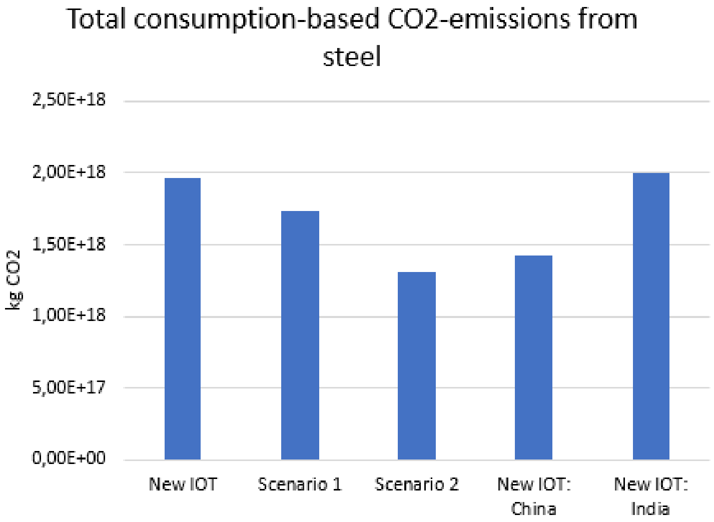


Figure 5.6: The total consumption-based CO_2-emissions for the current data and the two scenarios. In addition the current data with the share of EAF in China and then India is set to 75%. The new use-table and extensions are used after re-allocation. Calculation can be found in A.4.5 under section 5.1-5-6.

5.2 Origin of consumption-based CO_2-emissions from steel

As Wanga et al. (2009) reports, it is the emissions from the BF that is dominating for all the countries in Figure 5.7, except for India where coal is the primary emitter. Natural gas is also a big source of emissions in the European couturiers (including Russia) and in the United States. Natural gas can be used in the EAF to produce primary steel from DRI. As India utilises coal-based DRI in their EAF, the emissions can be mitigated by changing to natural gas. For the emission relevant energy carriers in India, the value for coal is 184 650 TJ while for natural gas it is 12 447 TJ. A shift here would then lead to a lower CO_2-emission intensity for India and consequently for the world as was made clear in Figure 5.6.

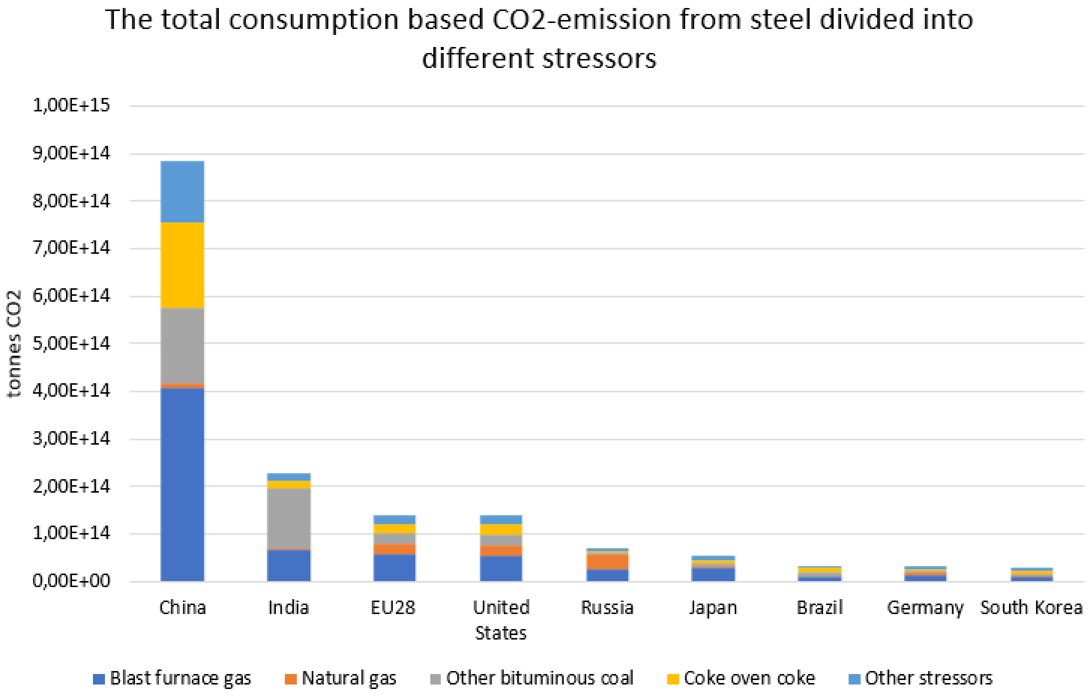


Figure 5.7: The total CO_2 consumption-based emission from steel due to the final demand of all industries, dividend into the stressors from which the emissions originate. Data from EXIOBASE in 2014 after re-allocation. Calculation can be found in A.4.5 under section 6.

5.3 The share of CO_2-emissions embodied in consumption from steel vs. other industries

1	Manufacture of basic iron and steel and of ferro-alloys and first products thereof	82,27 %
2	Re-processing of secondary steel into new steel	64,23 %
3	Manufacture of fabricated metal products, except machinery and equipment (28)	35,88 %
4	Manufacture of electrical machinery and apparatus n.e.c. (31)	30,39 %
5	Manufacture of other transport equipment (35)	29,49 %
6	Manufacture of machinery and equipment n.e.c. (29)	29,31 %
7	Manufacture of motor vehicles, trailers and semi-trailers (34)	24,33 %
8	Casting of metals	23,22 %
9	Construction (45)	16,36 %
10	Mining of copper ores and concentrates	14,90 %
11	Manufacture of radio, television and communication equipment and apparatus (32)	12,53 %
12	Manufacture of office machinery and computers (30)	12,43 %
13	Mining of uranium and thorium ores (12)	11,39 %
14	Waste water treatment, other	8,85 %
15	Manufacture of medical, precision and optical instruments, watches and clocks (33)	8,10 %
16	Waste water treatment, food	7,62 %
17	Landfill of waste: Food	7,15 %
18	Mining of other non-ferrous metal ores and concentrates	7,02 %
19	Landfill of waste: Paper	6,39 %
20	Mining of nickel ores and concentrates	6,34 %
21	Post and telecommunications (64)	6,32 %
22	Renting of machinery and equipment without operator and of personal and household goods (71)	6,17 %
23	Research and development (73)	6,09 %
24	Incineration of waste: Food	6,08 %
25	Incineration of waste: Paper	6,05 %
26	Landfill of waste: Inert/metal/hazardous	6,01 %
27	Computer and related activities (72)	5,97 %
28	Manufacture of fish products	5,75 %
29	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	5,70 %
30	Landfill of waste: Plastic	5,45 %

Table 5.1: The top 30 industries shares of CO_2-emissions from the steel industries vs. other industries. Data from EXIOBASE after re-allocation on 2014. Calculation can be found in A.4.5 under section 7.

The share of CO_2-emissions from steel embodied in consumption due to final demand in the top 30 industries from after the re-allocation is presented i Table 5.1. Number one and two on the list are the two steelmaking industries themselves, which is the same result as from the old use-table i Karlsen (2017). The internal emissions from the BF/BOF has increased with almost 13 percentage point, while it has decreased some for the EAF compared to the master project.

For the current data in the new use-table, only approximately 18% of the emissions in the BF/BOF industry come from other sources. The remaining emissions in the primary industry come from electricity production from coal, coke oven products and mining. For the EAF, the emissions originate from electricity production from coal, biomass and gas, as well as from the

BF/BOF industry as the primary steel is produced there and recycled in the EAF.

32% of the total consumption-based steel emissions are consumed in the construction sector. However, this only accounts for 16.36% of the total emissions in this industry. The second largest consumer of steel-emissions is the ”Manufacture of machinery and equipment n.e.c.“-industry at 16%. The industries that is manufacturing products, all have a significant amount of their CO_2-emissions originating from steel. These industries either produce products with long lifetimes (cars, trucks, various machinery, etc.) or smaller products (radios, television, mobile phones and other electrical apparatus) where it is difficult to fully recycle the steel without contamination. The long lifetimes can leads to big sinks in the scrap availability utilised in the secondary production. Pauliuk et al. (2011) predicts that in China there will be a sudden increase in the available scrap-stock that can be utilised in the EAF between 2025 and 2050. However, at this time, the stock is still being build up by primary production with a higher emission-intensity.

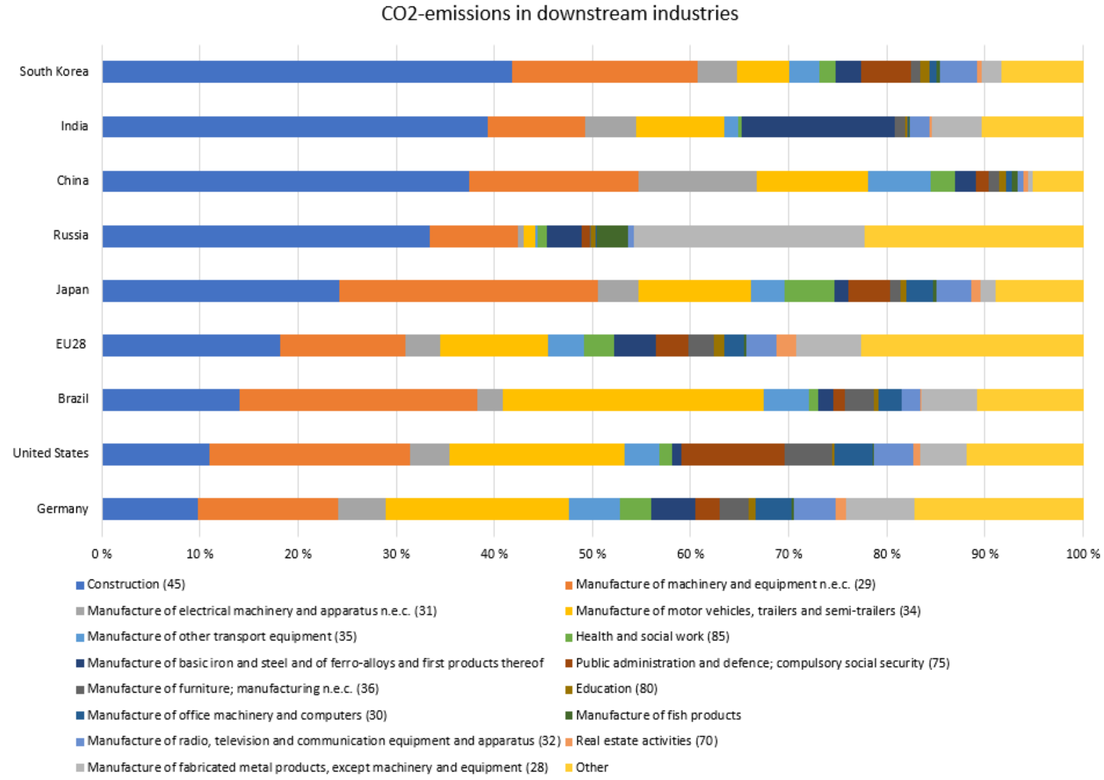


Figure 5.8: The CO_2-emission shares from steel for 15 industries and one aggregated for all industries in nine countries/regions. Data from EXIOBASE in 2014 after re-allocation. Calculation can be found in A.4.5 under section 7.

As mentioned, the construction industry consumes most of the total consumption-based emissions, but the share varies between the different EXIOBASE countries as Figure 5.8 shows.

Here, which industries the steel emission is consumed in can be observed for eight countries and the EU28. In the developing countries, most of the emissions goes into the construction industry, while Germany has the smallest share. With 19% the “Manufacture of motor vehicles, trailers and semi-trailers”-industry is the highest in Germany, as the country is the fourth largest producer of vehicles in the world.

For the United states,the “Public administration and defence; compulsory social security”-industry has nearly the same emission share as the construction-industry at 10% of the steel emissions. This industry includes defence, police and general administrations. From the total emissions from this industry due to steel, 26% end up in the United States. However, 21% is consumed in China, though it only represent 1% of the total Chinese steel-emissions.

5.4 What-if scenario analysis: Emissions embodied in consumption for downstream industries from steel

	Industry	**NU**	**NU-S1**	**NU-S2**
1	Manufacture of basic iron and steel and of ferro-alloys and first products thereof	82,27 %	6,50 %	19,42 %
2	Re-processing of secondary steel into new steel	64,23 %	-13,45 %	-22,25 %
3	Manufacture of fabricated metal products, except machinery and equipment (28)	35,88 %	5,31 %	8,96 %
4	Manufacture of electrical machinery and apparatus n.e.c. (31)	30,39 %	7,36 %	12,97 %
5	Manufacture of other transport equipment (35)	29,49 %	7,18 %	12,63 %
6	Manufacture of machinery and equipment n.e.c. (29)	29,31 %	6,87 %	11,91 %
7	Manufacture of motor vehicles, trailers and semi-trailers (34)	24,33 %	5,60 %	9,66 %
8	Casting of metals	23,22 %	1,63 %	1,96 %
9	Construction (45)	16,36 %	4,03 %	6,65 %
10	Mining of copper ores and concentrates	14,90 %	3,72 %	5,66 %
11	Manufacture of radio, television and communication equipment and apparatus (32)	12,53 %	3,51 %	5,87 %
12	Manufacture of office machinery and computers (30)	12,43 %	3,78 %	6,44 %
13	Mining of uranium and thorium ores (12)	11,39 %	3,58 %	6,13 %
14	Waste water treatment, other	8,85 %	2,71 %	4,59 %
15	Manufacture of medical, precision and optical instruments, watches and clocks (33)	8,10 %	2,25 %	3,74 %
16	Waste water treatment, food	7,62 %	2,29 %	3,87 %
17	Landfill of waste: Food	7,15 %	2,08 %	3,51 %
18	Mining of other non-ferrous metal ores and concentrates	7,02 %	1,95 %	3,15 %
19	Landfill of waste: Paper	6,39 %	1,89 %	3,17 %
20	Mining of nickel ores and concentrates	6,34 %	1,75 %	2,83 %
21	Post and telecommunications (64)	6,32 %	1,28 %	2,10 %
22	Renting of machinery and equipment without operator and of personal and household goods (71)	6,17 %	1,89 %	3,16 %
23	Research and development (73)	6,09 %	1,31 %	2,21 %
24	Incineration of waste: Food	6,08 %	1,95 %	3,28 %
25	Incineration of waste: Paper	6,05 %	1,94 %	3,25 %
26	Landfill of waste: Inert/metal/hazardous	6,01 %	1,78 %	2,99 %
27	Computer and related activities (72)	5,97 %	1,84 %	3,06 %
28	Manufacture of fish products	5,75 %	1,55 %	2,60 %
29	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	5,70 %	1,51 %	2,41 %
30	Landfill of waste: Plastic	5,45 %	1,58 %	2,66 %

Table 5.2: The comparison of the share in percentage points (pp) of CO_2-emission coming from the steel industries vs. other industries for the top 30 industries. The comparison is done between the current data after re-allocation (NU), scenario 1: realistic (S1) and scenario 2:BAT (S2). Calculation can be found in A.4.5 under section 7.

In Table 5.1 the consumption-based emissions share of steel was presented. Now, in Table 5.2, the percentage points (pp) of the share of consumption-based CO_2-emission from steel from the current data after the re-allocation are compared to the two scenarios (scenario 1: realistic and scenario 2: BAT). The only industry where the share of emissions from steel is higher in the scenarios than in the current data, is the EAF industry. It increases with subsequently 13.45 pp and 22.25 pp from the current data to the scenarios. All emissions shares from steel, as well as the total CO_2-emissions, in the industries in Table 5.2 have decreased.

In scenario 1: realistic it is the ”Manufacture of electrical machinery and apparatus n.e.c.“-industry that has the highest decrease in percentage point. Apart from the steel industries themselves, it is the same industry that experiences the highers decrease in percentage points for scenario 2: BAT as well. This is a industry producing electrical machines, cable, transformer, batteries, etc. (United Nations Statistical Commission 2002). The other manufacturing industries also experience decreases in their percentage points compared to the current data.

The small decrease in the ”Casting of metals“-industry compared to the other large steel emission industries, can be due to the fact that the total production of steel is unchanged. The same amount of steel needs to be cast, no matter which industry produces it. The casting-industry has improved vastly over the years as continues casting was introduced. Still, some countries produce ingots that needs to be remelted before casting. This increased the energy-intensity, and by default the emission-intensity, for the steelmaking. An example of this is India, where more than 17% of the liquid metal was cast into ingots. In 2000, 13% of all crude steel production was cast in to ingots. In 2014, however, the share had decreased to only 3.7% (World Steel Association (2016) and World Steel Association (2000)).

5.5 What-if scenario analysis: The change in total CO_2 consumption-based emissions in the manufacturing sector and construction

Figure 5.9 shows the total consumption-based CO_2-emissions for the most influential manufacturing industries and the construction industry as opposed to the share from steel in Table 5.1 and 5.2. The manufacturing industries were chosen as these are the industries producing products that are in high demand and as the changes observed in Table 5.2 were among the largest. The regular consumer does not buy steel directly from the plant, or copper from copper ores. They buy item containing steel and copper. Looking at the final demand-vector, all the manufacturing industries are among the top 35 industries. Construction is comes second in the total final demand, after ”Public administration and defence; compulsory social security“.

The industry from Figure 5.9 with the biggest change is the ”Manufacture of electrical machinery and apparatus n.e.c.“-industry with 10% change from the current to scenario 1: realistic and 16% to scenario 2: BAT. In Table 5.1 this was the industry with the biggest decrease in percentage points (excluding the steel industries themselves).

The biggest decrease in total, was observed in the construction-industry. The potential in the construction sector are a lot higher than by only a technological shift. Even though the lifetime of buildings, bridges, infrastructure, etc. can be very long, the potential for reuse, not recycling, of components made from steel, could be considerable.

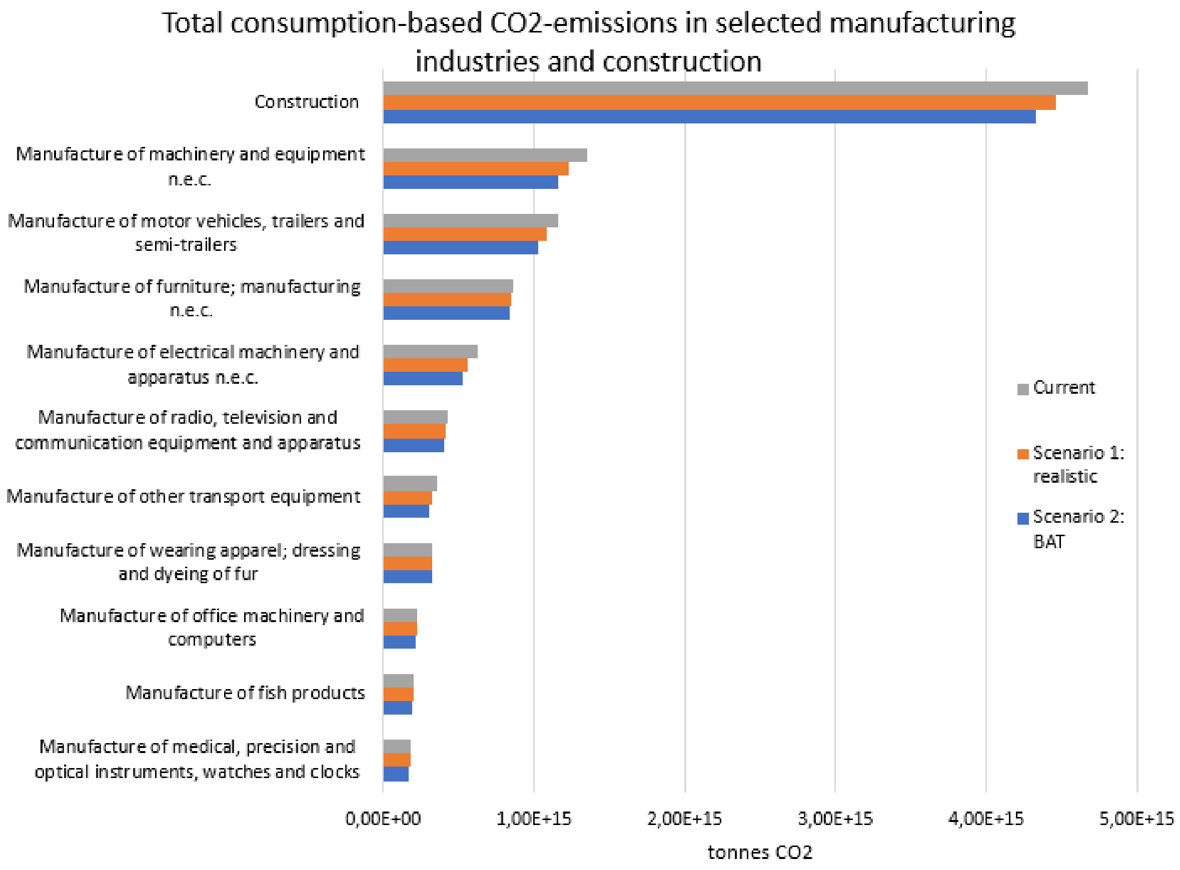


Figure 5.9: The total consumption-based CO_2-emissions in ten manufacturing industries for the current situation, scenario 1: realistic and scenario 2: BAT. Data from EXIOBASE for all countries after re-allocation. Calculation can be found in A.4.5 under section 7.

For the total emission reduction, the CO_2 consumption-based emissions has decreased with 3% from the current to scenario 1: realistic and with 4% to scenario 2: BAT. However, when only considering the emissions from the steel industries, the decrease is 12% from the current to scenario 1: realistic and 33% to scenario 2: BAT. This is almost equal to the projected global emissions reduction potential of the steel at 34% reported by Allwood et al. (2010). It is not fully the 50% reduction required. The results imply that the to reach the global emissions goal, some version resembling scenario 2: has to be implemented. However, as this is not a realistic scenario, improvements in the technology and investments in to the energy sector must be done to help reduce the global emissions by lowering the emission-intensities.

5.5.1 Manufacture of motor vehicles, trailers and semi-trailers

From Figure 5.9 the decrease in the ”Manufacture of motor vehicles, trailers and semi-trailers“-industry was 7% from current to scenario 1: realistic and 11% from current to scenario 2: BAT. China, the United States, Japan and Germany are the top four car-producing countries (ACEA 2018).

The biggest change is in China. This is the result of the change in the share of the EAF and the difference in the emission-intensity for China between the BF/BOF and EAF being higher than for the other presented countries.

The high emissions in China is troubling. Along with the higher quality of life the Chinese population is experiencing, the consummation of vehicles will increase. A car will in addition to the emissions from the production process continue to emit GHG throughout its lifetime. Even though electrical cars are becoming more effective, as the Chinese electricity is mostly based on coal, and as Hawkins et al. (2013) concludes that electric vehicles powered by coal-based electricity is counterproductive, this does not seem to be the solution.

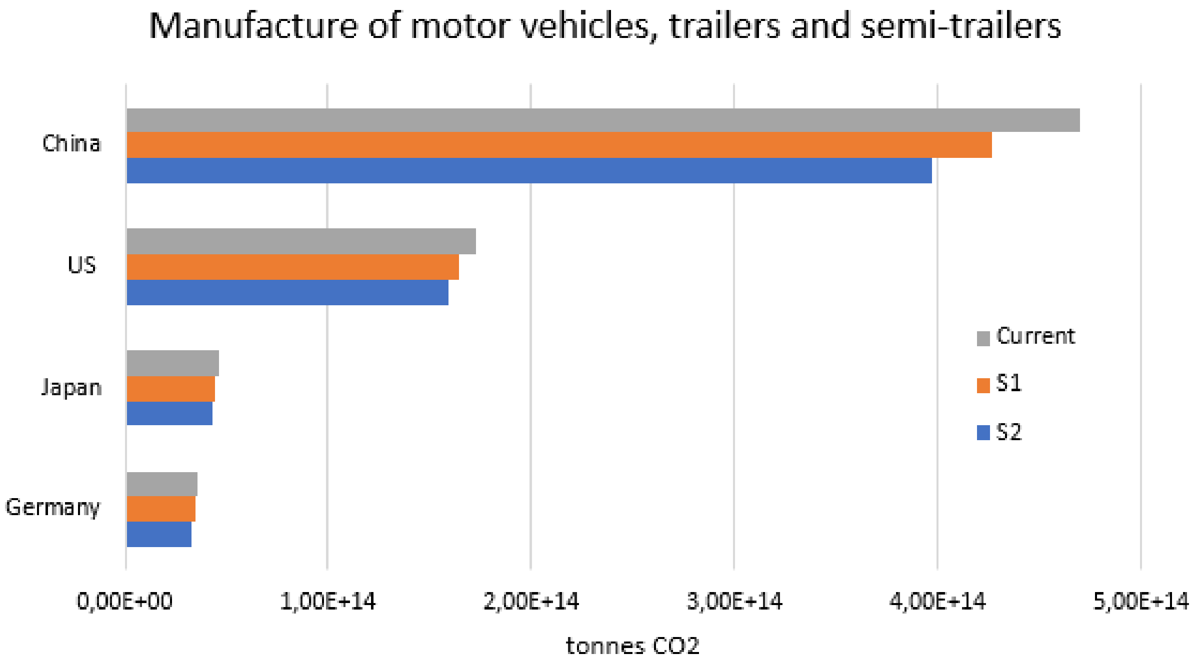


Figure 5.10: The total consumption-based CO_2-emissions the in ”Manufacture of motor vehicles, trailers and semi-trailers“ industry for the current situation, scenario 1: realistic and scenario 2: BAT for the top four car producing countries in the world (ACEA 2018). Data from EXIOBASE after re-allocation. Calculation can be found in A.4.5 under section 7.

6. Conclusion & Further Research

This master thesis presents a comprehensive literature summery on the energy use and emissions in the steel industry. From this literature it becomes clear that it is not solely the specific technology that determines the emission-intensity of the produced steel, the power input and the materials used must be considered as well. In addition, literature on the future of steel, the prediction of consumption and scrap, is presented.

In Karlsen (2017) the emission-intensities of the EAF were found to be higher for the majority of the countries than the emission-intensity for the BF/BOF. An thorough investigation of the EXIOBASE data was done, and the result of the re-allocations of the products in the use-table were presented and analysed. The emission-intensities after the data work was more in league with the literature, and the emission-intensities of the BF/BOF was now higher than for the EAF. The predicted shares of the top steel producing couturiers were necessary to find to analyse the effect a shift in the technology could have for the global impact.

The results of the share of emissions from steel in the other industries, showed that the higher the share of EAF, the lower the emissions from steel embodied in final consumption. For scenario 2: BAT there was a 33% decrease in the consumption-based CO_2-emissions. This is almost equal to the projected global emissions reduction potential of the steel at 34% reported by Allwood et al. (2010). However, for the most realistic scenario the decrease was at only 12%.

Several of the manufacturing industries were among the industries with the largest decreases in percentage points of emissions from steel. These are the industries producing products the the regular consumer buys. For the car-industry the biggest reductions where in China.

The total global impact of the changes made in the two scenarios led to a decrease of 3-4% in the total consumption-based CO_2 emissions. However, with more research into the specific countries to find the most effective individual changes, a more significant reduction can be achieved. To further reduce the emissions without a shift in the technology, already existing improvements can be made to the industries as well as CCS. In addition, investments in the energy sector to lower the emission-intensities of the power sector can be effective.

If a similar decease in the CO_2-emissions from the steel industry that presented here can be implemented in to the other high-emitting industries (cement, paper, plastic and aluminium), there is a chance the global goal at 50% reduction in the industrial sector can be met. Furthermore, the future is uncertain. There might be invented technologies that can lead to critical advanced on the global scale.

For further research, the industries in EXIOBASE can be disaggregated to locate the characteristics of the steel technologies to make sure they are accurately reflected.

To further improve the scenarios presented here could also be helpful. To look more closely at the countries and create individual changes in the extensions to see the effect. This is particularly interesting for India, where a possible change from coal-based DRI to using natural gas for the reduction process, could yield positive results.

In addition, it could be interesting to see how re-use of steel, without destruction, could effect the construction industry.

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A. Appendix

A.1 Steel technologies[1]

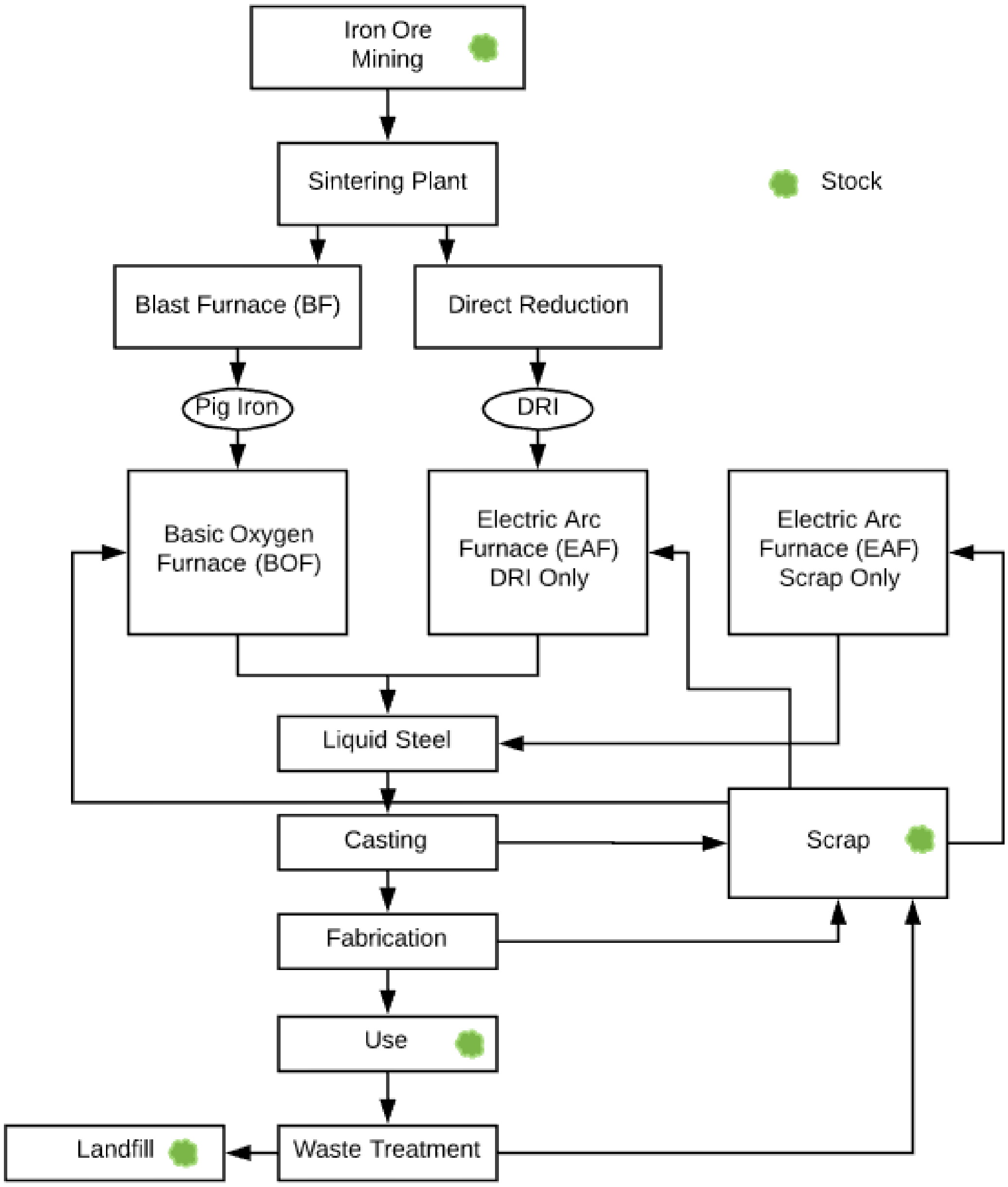

Figure A.1: A simplified flow-chart of the steelmaking process.

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[1] This section (excluding Figure A.1) is taken from Karlsen (2017)

A.1.1 Integrated Blast Furnace/Basic Oxygen Furnace (BF/BOF)

The BF/BOF combines the blast furnace (BF) and basic oxygen steelmaking (BOF). In the BF, coke is used as a power source. Coke is a product produced from various types of coal that contains 90-93% carbon, and has a high energy value compared to raw coal (Ricketts 2017). Coke can either be purchased from outside sources or it can be produced on site by heating coal in a coke oven without the presence of air. If the coke oven is on-site, the gas from the process can be fed into the BF to induce the efficiency (OECD 2001). The BF is usually charged with sinter plants or pellets of iron ore, coke and limestone (flux) in turns. Then the blast, a hot steam of air, is blown into the furnace from the bottom and reduces the iron ore to pig iron (OECD 2001). The flux is present to melt and become slag which removes sulfur and other impurities from the pig iron (Ricketts 2017).

Next, the pig iron is tapped and transferred into the BOF where oxygen is blown into the molten pig iron to remove carbon and further purify it (OECD 2001). The oxygen lowers the carbon content by reacting with the carbon to form CO and CO_2 (Stubbles 2017). When the steel has reached the desired grade, it will be cast. This can be done either continuously or the steel can be cast into an ingot. In a separate process the ingot can be remelted before finishing, which leads to additional energy use compared to continuous casting (OECD 2001).

The basic oxygen steelmaking replaced the OHF in the mid 20th century and most of the OHFs in the world were closed down. There are still some furnaces in operation in Ukraine and Russia at present (World Steel Association (2012) and World Steel Association (2017)).

A.1.2 Electric Arc Furnace (EAF)

The EAF operates in a cycle called tap-to-tap. This cycle includes charging of the furnace, melting, refining, de-slagging , tapping and furnace turn-around (Jones 2017).

A bucket of scrap, heavy melt and flux is poured into the open furnace before the roof is closed and the electrodes are lowered into the scrap. The EAF uses electricity to form an electric arc between the charged material and the electrodes with a power of 50-80 MW. The temperature of the arc can reach 3 500°C (Haderaa et al. 2015), and the pig iron can reach 1 800°C. Oxygen is blown into the furnace during refining, and natural gas can be added to speed up the process. When enough of the first charge has melted, the charging process can be repeated until the quality of the steel is tested and determined to be ideal. The furnace is then tilted to one side and the slag is removed, before it is tilted to the other side and the molten steel is tapped (Gajic et al. 2016). The quality of the steel produced from the EAF can be lower than steel from the BF/BOF because of contamination in the scrap (OECD 2001).

Of the total world steel production in 2014, 25.8% (World Steel Association 2016) is done in the EAF. Because the EAF can produce steel with different grades from several different materials and because it is powered by electricity and chemical energy, this technology is becoming the main steelmaking technology to replace the outdated OHF and the BF/BOF (Kirschen et al. 2009). The EAF also comes in different sizes, from minimills to larger ones, but Chen et al. (2017) concludes that the use of larger furnaces will be most energy and cost effective. The fact that the EAF can make steel from 100% scrap metal reduces the energy needed compared with the BF/BOF. If the EAF is using Directly Reduced Iron (DRI) the energy consumption and emissions are a bit higher, but still lower than for a BF/BOF. The EAF is for the most part charged with scrap, but about 3% of the total steel production comes from EAFs charged with directly reduced iron (DRI) produced from natural gas (Newman 2010). **To produce DRI a shaft furnace is used to directly reduce the iron ore producing sponge iron. The sponge iron together with scrap is then processed in the EAF (Pardo et al. 2012).**

A.1.3 Open Hearth Furnaces (OHF)

The open hearth furnace (OHF), also called the Siemens-Martin furnace or process, was the main steelmaking technology for most of the 20th century. The furnace burns carbon out of pig iron, or scrap, to produce steel. The OHF is charged with light scrap and heated with burning gas. When the light scrap is melted, heavy scrap and pig iron (produced in a blast furnaces) are added. When this has melted the limestone is added to form slag (Cabrera et al. 2014).

The OHF technology has been replaced by other technologies in most of the world, and in 2014 only 0.5% of the worlds steel production used this route. In 2012 there was only seven OHFs left (World Steel Association 2012). In 2014, only three steel producing countries still used the OHF: Ukraine with 20.5%, Russia with 2.8% and India with 0.1% (World Steel Association 2016). In 2016 Ukraine's share had fallen to 2.4%, Russia's increased to 21.4%, while in India there was no more steel produced from the OHF (World Steel Association 2017).

A.2 Re-allocations of the use- and use-coefficient-table

Data from Sandberg et al. (2001) was used as an indication of how to re-allocate the products in the use-table. As the energy-use of the BF/BOF is higher than in the EAF, re-allocations between the two technologies were needed. Electricity is used as a power source in the EAF and the BF/BOF utilizes coal-based energy.

All coal-based products (numbers 20, 21, 22, 23, 24, 64, 66, 83 and 91 in Table A.1) can be allocated from the EAF to the BF/BOF. However, for countries like India and Indonesia where DRI-EAF is used, the EAF will need use of coal-based products.

For ”Iron ores“ and ”Secondary raw materials“ (scrap metal) most of the iron ore can be allocated to the BF/BOF and the scrap can be allocated to the EAF. Again here for countries that use DRI, iron ore will be used in the EAF. According to Figure A.1 scrap can be used in the BF/BOF and iron ore in the EAF. As explained in 4.2.2 the balances of the column-sums has to match, so these two products can be used to adjust the column-sums. Because of this, some of the shares in Table A.1 can not be followed methodically.

The majority of the electricity (product numbers 129-139 in Table A.1) use should be allocated to the EAF. Even though the BF/BOF does not use electricity in the steel production, there will be use of electricity for light, computers, heating etc.

The last three rows in Table A.1 show gases from, mainly, the BF/BOF route. Use of ”Coke oven gas“ and ”Oxygen Steel Furnace Gas“ should be fully reallocated to the BF/BOF industry. For the ”Blast Furnace Gas“ a small amount could be allocated to the EAF as the DRI-EAF-route will need a BF. For the ”Coke oven gas“ there will only be use if the coke oven is on the BF/BOF plant.

Table A.1: New allocation percentages for the changes in the use-table.

#	Product	BF/BOF	EAF
20	Anthracite	95 - 100 %	0 - 5 %
21	Coking Coal	95 - 100 %	0 - 5 %
22	Other Bituminous Coal	95 - 100 %	0 - 5 %
23	Sub-Bituminous Coal	95 - 100 %	0 - 5 %
25	Lignite/Brown Coal	95 - 100 %	0 - 5 %
33	Iron ores	99 - 100 %	0 - 1 %
64	Coke Oven Coke	95 - 100 %	0 - 5 %
66	Coal Tar	95 - 100 %	0 - 5 %
83	Petroleum Coke	95 - 100 %	0 - 5 %
91	Charcoal	95 - 100 %	0 - 5 %
126	Secondary raw materials	0 - 20 %	80 - 100 %
129	Electricity by gas	20 - 30 %	70 - 80 %
130	Electricity by nuclear	20 - 30 %	70 - 80 %
131	Electricity by hydro	20 - 30 %	70 - 80 %
132	Electricity by wind	20 - 30 %	70 - 80 %
133	Electricity by petroleum and other oil derivatives	20 - 30 %	70 - 80 %
134	Electricity by biomass and waste	20 - 30 %	70 - 80 %
135	Electricity by solar photovoltaic	20 - 30 %	70 - 80 %
136	Electricity by solar thermal	20 - 30 %	70 - 80 %
137	Electricity by tide, wave, ocean	20 - 30 %	70 - 80 %
138	Electricity by Geothermal	20 - 30 %	70 - 80 %
139	Electricity nec	20 - 30 %	70 - 80 %
142	Coke oven gas	100 %	0 %
143	Blast Furnace Gas	99 - 100 %	0 - 1 %
144	Oxygen Steel Furnace Gas	100 %	0 %

A.3 World Population in 2014

The population of the EXIOBASE countries are presented in Table A.2 in thousand people. Knowing the population of the countries that are present in the EXIOBASE database, can make the results of for example the emission embodied in consumption more comparable to each other on a per capita level. This is done in section 5.1.

Country	Population	Country	Population
China	1 397 894	Greece	11 265
India	1 293 859	Belgium	11 219
United States	317 719	Czech Republic	10 599
Indonesia	255 131	Portugal	10 471
Brazil	204 213	Hungary	9 813
Russia	143 761	Sweden	9 689
Japan	128 163	Austria	8 633
Mexico	124 222	Switzerland	8 230
Germany	81 490	Bulgaria	7 222
Turkey	77 031	Denmark	5 664
United Kingdom	65 016	Finland	5 460
France	64 191	Slovakia	5 433
Italy	59 586	Norway	5 140
South Africa	54 540	Ireland	4 686
South Korea	50 386	Croatia	4 258
Spain	46 522	Lithuania	2 962
Poland	38 293	Slovenia	2 071
Canada	35 605	Latvia	2 016
Australia	23 475	Estonia	1 318
Taiwan	23 414	Cyprus	1 152
Romania	19 973	Luxembourg	556
Netherlands	16 889	Malta	426

Table A.2: The world population in 2014 in a thousand people (United Nations 2017)

A.4 MatLab-scripts

A.4.1 Steel Demand Function

```
function [steel_tot, BOF_tot, EAF_tot,share_BOF, share_EAF] = SteelDemand(a)

load (a)

ncou     = meta.NCOUNTRIES;  % number of countries
nind     = meta.NSECTORS;    % number of industries

x2       = zeros(ncou,nind);

for q = 1:ncou
    x_mid = x(nind*(q-1)+1:q*nind);
    x2(q,:) = x_mid';
end

b            = sum(x2);
steel_tot    = b(72) + b(73);    % Total steel output
BOF_tot      = b(72);            % Output of BF/BOF
EAF_tot      = b(73);            % Output of EAF

BOF_output = x2(:,72);
EAF_output = x2(:,73);
steel_output = BOF_output+EAF_output;
share_BOF = BOF_output./steel_output;
share_EAF = EAF_output./steel_output;

end
```

A.4.2 Emissions Relevant Energy Carriers and CO_2 combustion data for BF/BOF, EAF and mining of iron ores for new and old extensions

```
function [EREC_BOF, EREC_EAF, CO2_combustion_all_countries, mining, stressor_BOF, stressor_EAF, EREC_BOF_new, EREC_EAF_new] = EREC(A,B)
 load(A);

ncou    = meta.NCOUNTRIES;  % number of countries
nind    = meta.NSECTORS;    % number of industries
nstre   = meta.Fdim;        % number of old stressors
bof     = 72;               % number of industry BF/BOF
eaf     = 73;               % number of industry EAF

%% Old extensions
S1 = zeros(nstre,nind,ncou);
F2 = zeros(1338,nind,ncou);
% Making the S-matrix 3-dimentional
for i= 1:ncou
    S1(:,:,i) = IO.S(:,nind*(i-1)+1:i*nind);
    F2(:,:,i) = F(:,nind*(i-1)+1:i*nind);
end

% The emission relevant energy carriers
EREC_BOF = zeros(56,ncou);
EREC_EAF = zeros(56,ncou);
EREC_BOF_S = zeros(56,ncou);
EREC_EAF_S = zeros(56,ncou);

for i = 1:ncou
    EREC_BOF_S(:,i) = S1((491:546), bof,i);
    EREC_EAF_S(:,i) = S1((491:546), eaf,i);
    EREC_BOF(:,i) = F2((491:546), bof,i);
    EREC_EAF(:,i) = F2((491:546), eaf,i);
end


% Picking out the CO2-combustion for all countries
CO2_combustion_all_countries = zeros(ncou,2);
for i = 1:ncou
    CO2_combustion_all_countries(i,1) = S1(24,bof,i);
    CO2_combustion_all_countries(i,2) = S1(24,eaf,i);
end
```

```
% Looking at the emissions of CO2 from mining of iron ores
mining = zeros(ncou,1);
for i = 1:ncou
      mining(i,1) = S1(24,25,i);
end

%% New extensions
load (B)
nstre   = 260;              % number of new stressors
ncou = 49;
nind = 163;

stressor_BOF     = zeros(nstre,ncou);
stressor_EAF     = zeros(nstre,ncou);
stressors        = zeros(nstre,2,ncou);


for p = 1:ncou
    e_i(:  ,:  , p) = extensions_industry(1:nstre, (p-1)*nind +1:p*nind);
end

for i= 1:ncou
    stressor_BOF(:,i) = e_i(:,bof,i);
    stressor_EAF(:,i) = e_i(:,eaf,i);
end

for i = 1:ncou
    stressors(:,1,i) = e_i(:,72,i);
    stressors(:,2,i) = e_i(:,73,i);
end


% The stressor matrix for the new extensions.
extensions_industry_per_output = zeros(size(extensions_industry));
stressor_per_output_BOF   = zeros(nstre,ncou);
stressor_per_output_EAF   = zeros(nstre,ncou);

for i = 1:260
    extensions_industry_per_output(i,:) = extensions_industry(i,:)./transpose(x);
end

for p = 1:49
    e_i_per_output(:  ,:  , p) = extensions_industry_per_output(1:nstre, (p-1)*nind +1:p*
    nind);
end
```

```


for  i= 1:49
      stressor_per_output_BOF(:,i) = e_i_per_output(:,bof,i);
      stressor_per_output_EAF(:,i) = e_i_per_output(:,eaf,i);
end
stressor_per_output_BOF(isnan(stressor_per_output_BOF))=0;
stressor_per_output_EAF(isnan(stressor_per_output_EAF))=0;

EREC_BOF_new = stressor_per_output_BOF(131:195,:);
EREC_EAF_new = stressor_per_output_EAF(131:195,:);

end
```

A.4.3 Functions for emission-intensities for new and old extension

Old extension

```
function [emission_intensity_BOF,emission_intensity_EAF] =  MFEI(B)

load (B)

ncou     = meta.NCOUNTRIES;  % number of countries
nind     = meta.NSECTORS;    % number of industries
bof      = 72;               % number of industry BF/BOF
eaf      = 73;               % number of industry EAF


%% 2 Extract GHG emission rows from stressor matrix IO.S IO.F./IO.x (nghg x nind x ncou)
ghgindex         = find(C(9,:));
nghg             = length(ghgindex);
SGHGemissions    = zeros(nghg,nind,ncou);
SGHGemissions1   = zeros(nghg, nind*ncou);

% 2.1 First two-dimensional matrix
for s = 1:nghg
   SGHGemissions1(s,:) = S(ghgindex(s),:);
end

% 2.2 Three-dimesional
for p = 1:ncou
    SGHGemissions(:  ,:  , p) = SGHGemissions1(1:nghg, (p-1)*nind +1:p*nind);
end
%% 5 Compare the emission intensities of 72 and 73 across countries

emissions49      = zeros(nghg, nind,ncou);
emissionsBOF     = zeros(1,1,ncou);
emissionsEAF     = zeros(1,1,ncou);

char1  = C(9,:);             % Characterisation matrix row 9 for GHG emission
char22 = char1(char1 ~= 0); % Elimenate the 0's from the vector

% 5.2 Convert the emissions from IO.S to CO2-equivalents
for i= 1:ncou
    for p = 1:nghg
        for r= 1:nind
            emissions49(p,r,i) = SGHGemissions(p, r, i) .*char22(p);
        end
```

```
    end
end
emissions49 = sum(emissions49);  % Sum the columns

% 5.3 The emissions related to steel:
for i = 1: ncou
   emissionsBOF(1,:,i) = emissions49(1,bof,i);
   emissionsEAF(1,:,i) = emissions49(1,eaf,i);
end
emission_intensity_BOF= squeeze(emissionsBOF);  % Emission intencities per country for BOF
emission_intensity_EAF= squeeze(emissionsEAF);  % Emission intencities per country for BOF

end
```

New extension

```
function [emission_intensity_BOF_new,emission_intensity_EAF_new] = NewMFEI(B, F)

load (B)
load (F);

ncou    = 49;               % number of countries
nind    = 163;              % number of industries
nstre   = 260;              % number of stressors
bof     = 72;               % number of industry BF/BOF
eaf     = 73;               % number of industry EAF


emission_intensity_BOF    = zeros(nstre,ncou);
emission_intensity_EAF    = zeros(nstre,ncou);


for p = 1:ncou
    e_i(:  ,:  , p) = extensions_industry(1:nstre, (p-1)*nind +1:p*nind);
end

for i= 1:ncou
    emission_intensity_BOF_new(:,i) = e_i(:,bof,i);
    emission_intensity_EAF_new(:,i) = e_i(:,eaf,i);
end



end
```

A.4.4 Supply- and Use-Table

```
%% Supply-Use-Tables
% filenameOUT = 'MRSUT.xlsx';
filenameIN = 'Master input from MatLab.xlsx';
FilenameIN2 = 'Shares for master.xlsb';

% load('MRSUT_2011.mat')
nprod = 200;
nind  = 163;
ncou  = 49;
bof   = 72;
eaf   = 73;


%% 1. Create full Use-Table with domestic and import

MRUSE = MRSUT.mrbpdom + MRSUT.mrbpimp;

% 1.1 The total industry output (x)
industry_output = sum(MRUSE,1) + sum(MRSUT.mrbpdomva,1);

% 1.2 The Use-coefficient matrix
MRUSE_coeff  = zeros (size(MRUSE));
for i = 1:ncou*nprod
    MRUSE_coeff(i,:) = MRUSE(i,:)./industry_output;
end

MRUSE_coeff(isnan(MRUSE_coeff))=0;



%% 2. Reformate the Use-Table

MRUSE_3dim = zeros(nprod,nind,ncou);
USE2 = zeros(nprod, nind*ncou);

MRUSE_coeff_3dim = zeros(nprod,nind,ncou);
USE2_coeff = zeros(nprod, nind*ncou);

% 2.1 first: get a two-dimensional matrix of size nprod x (nind*ncou)
for i= 1:nprod
    for r = 1:ncou
    indx_USE =nprod*(r-1)+i;
```

```

    USE_mid = MRUSE(indx_USE,:);
    USE2(i,:) = USE2(i,:) + USE_mid;

    USE_coeff_mid = MRUSE_coeff(indx_USE,:);
    USE2_coeff(i,:) = USE2_coeff(i,:) + USE_coeff_mid;
    end
end

% 2.3 second: reformat that two dimensional matrix into the 3 dimensional cube
for p = 1:ncou
    MRUSE_3dim(:  ,:  , p) = USE2(:, (p-1)*nind +1:p*nind);
    MRUSE_coeff_3dim(:  ,:  , p) = USE2_coeff(:, (p-1)*nind +1:p*nind);
end

%% 3. Collect the steel data from the USE matrix

USE_steel1 = zeros(nprod, 2, 2*ncou);
USE_steel = zeros(nprod, 2*ncou);

for i = 1:ncou
    USE_steel1(:,1,i) = MRUSE_3dim(:,72,i);
    USE_steel1(:,2,i) = MRUSE_3dim(:,73,i);
end

% 3.1 Make it 2-dimetional
for i = 1:ncou
    USE_steel(:,2*i-1) = USE_steel1(:,1,i);
    USE_steel(:,2*i) = USE_steel1(:,2,i);
end

for i = 1:ncou
    USE_steel_BOF(:,i) = MRUSE_3dim(:,72,i);
    USE_steel_EAF(:,i) = MRUSE_3dim(:,73,i);
end




%% 4. Collect the steel data from the coefficient matrix

USE_coeff_steel1 = zeros(nprod, 2, 2*ncou);
USE_coeff_steel = zeros(nprod, 2*ncou);

for i = 1:ncou
```

```
    USE_coeff_steel1(:,1,i) = MRUSE_coeff_3dim(:,72,i);
    USE_coeff_steel1(:,2,i) = MRUSE_coeff_3dim(:,73,i);
end

% 4.1 Make it 2-dimetional
for i = 1:ncou
    USE_coeff_steel(:,2*i-1) = USE_coeff_steel1(:,1,i);
    USE_coeff_steel(:,2*i) = USE_coeff_steel1(:,2,i);
end


%% 5. Trade shares for steel

USE_BOF = zeros(nprod*ncou,ncou);
USE_EAF = zeros(nprod*ncou,ncou);
USE_BOF_total = zeros(nprod*ncou,ncou);
USE_EAF_total = zeros(nprod*ncou,ncou);
USE_BOF_share = zeros(nprod*ncou,ncou);
USE_EAF_share = zeros(nprod*ncou,ncou);

for r = 1:ncou
    USE_BOF(:,r) = MRUSE(:,(r-1)*nind+72);
    USE_EAF(:,r) = MRUSE(:,(r-1)*nind+73);
end

for r = 1:ncou
    for i = 1:ncou
    USE_BOF_total(((i-1)*nprod+1):(i*nprod),r) = MRUSE_3dim(:,72,r);
    USE_EAF_total(((i-1)*nprod+1):(i*nprod),r) = MRUSE_3dim(:,73,r);
    end
end

for i = 1:ncou
    USE_BOF_share(:,i) = USE_BOF(:,i)./USE_BOF_total(:,i);
    USE_EAF_share(:,i) = USE_EAF(:,i)./USE_EAF_total(:,i);
end

USE_BOF_share(isnan(USE_BOF_share))=0;
USE_EAF_share(isnan(USE_EAF_share))=0;

% 5.1 test if all product share sums are 1 or 0
test1 = zeros(200,49);
for r = 1:200
    for i=1:ncou
        test1(r,i) = sum(USE_BOF_share(r:200:end,i));
```

```
    end

end


%% 6. Create new MRSUT
NewMRUSE_2014 = MRUSE;
NewBOF_EAF_USE = xlsread(filenameIN, 'NewMRSUT', 'B2:CU201');
NewUSE_BOF = zeros(nprod*ncou,ncou);
NewUSE_EAF = zeros(nprod*ncou,ncou);
j = 1;
for r = 1:ncou

    for i = 1:ncou
    NewUSE_BOF(((i-1)*nprod+1):(i*nprod),r) = NewBOF_EAF_USE(:,j);
    NewUSE_EAF(((i-1)*nprod+1):(i*nprod),r) = NewBOF_EAF_USE(:,j+1);
    end
j = j+2;
end

for i = 1:2:ncou
    USE_steel_BOF_new(:,i) = NewBOF_EAF_USE(:,i);
    USE_steel_EAF_new(:,i) = NewBOF_EAF_USE(:,i+1);
end



for r = 1:ncou
    NewMRUSE_2014(:,((r-1)*nind + 72)) = USE_BOF_share(:,r).*NewUSE_BOF(:,r);
    NewMRUSE_2014(:,((r-1)*nind + 73)) = USE_EAF_share(:,r).*NewUSE_EAF(:,r);
end


%% 7. Make new struct for new use-table

New_MRSUT.mrbpdom = zeros(size(NewMRUSE_2014));
New_MRSUT.mrbpdomfd = MRSUT.mrbpdomfd;
New_MRSUT.mrbpimpfd = MRSUT.mrbpimpfd;
New_MRSUT.mrbpdomva = MRSUT.mrbpdomva;
New_MRSUT.year = 2014;
New_MRSUT.meta = MRSUT.meta;
New_MRSUT.mrsup = MRSUT.mrsup;

for i = 1:ncou
    New_MRSUT.mrbpdom((((i-1)*nprod+1):(i*nprod)),(((i-1)*nind+1):(i*nind))) =
```

```
    NewMRUSE_2014((((i-1)*nprod+1):(i*nprod)),(((i-1)*nind+1):(i*nind)));
end

New_MRSUT.mrbpimp = NewMRUSE_2014- New_MRSUT.mrbpdom;

New_MRSUT.mrbpdom(isnan(New_MRSUT.mrbpdom))=0;
New_MRSUT.mrbpimp(isnan(New_MRSUT.mrbpimp))=0;


%% 7. Scenario 1: realistic scenario

% 7.1 All things connected to use-table are equal to the new ust-table
New_MRSUT_1.mrbpdom = New_MRSUT.mrbpdom;
New_MRSUT_1.mrbpdomfd = New_MRSUT.mrbpdomfd;
New_MRSUT_1.mrbpimpfd = New_MRSUT.mrbpimpfd;
New_MRSUT_1.mrbpdomva = New_MRSUT.mrbpdomva;
New_MRSUT_1.year = 2014;
New_MRSUT_1.meta = New_MRSUT.meta;
New_MRSUT_1.mrbpimp = New_MRSUT.mrbpimp;
New_MRSUT_1.mrbpdom = New_MRSUT.mrbpdom;

% 7.1 modifying the supply table

New_MRSUT_1.mrsup = New_MRSUT.mrsup;

% supply to the steel technologies comes from product 104:
%'Basic iron and steel and of ferro-alloys and first products thereof'
 product_steel = 104;

% 7.2 Market share for steel of products 104

 market_share = New_MRSUT.mrsup./sum(New_MRSUT.mrsup,2);
 market_share(isnan(market_share))=0;

 market_share_bof = market_share(product_steel:nprod:end,bof:nind:end);
 market_share_bof = sum(market_share_bof,2);

 market_share_eaf = market_share(product_steel:nprod:end,eaf:nind:end);
 market_share_eaf = sum(market_share_eaf,2);
 market_share_tot = market_share_eaf + market_share_bof;

% 7.3 Collecting the total supply of each country

 supply_steel = zeros(ncou,2);

```

```
for i = 1:ncou
    supply_steel(i,1) = MRSUT.mrsup((i-1)*nprod + product_steel,(i-1)*nind+bof);
    supply_steel(i,2) = MRSUT.mrsup((i-1)*nprod + product_steel,(i-1)*nind+eaf);
end

% 7.4 The new steel shares
New_share = xlsread(FilenameIN2, 'New shares', 'G6:H54');

supply_steel_new = zeros(ncou,2);

for i = 1:ncou
    supply_steel_new(i,1) = New_share(i,1)*(supply_steel(i,1)+supply_steel(i,2));
    supply_steel_new(i,2) = New_share(i,2)*(supply_steel(i,1)+supply_steel(i,2));
end


for i =1:ncou
    New_MRSUT_1.mrsup((i-1)*nprod + product_steel,(i-1)*nind+bof) = supply_steel_new(i,1);
    New_MRSUT_1.mrsup((i-1)*nprod + product_steel,(i-1)*nind+eaf) = supply_steel_new(i,2);
end

% 7.5 now make new IOT for calculations using "PrepareMRSUTandCREATEixi.m"

%% 8. Scenario 2: the average share of BF/BOF and EAF that is 64,81% for BF/BOF and 35,19% for EAF


% 8.1 All things connected to use-table are equal to the new ust-table
New_MRSUT_2.mrbpdom = New_MRSUT.mrbpdom;
New_MRSUT_2.mrbpdomfd = New_MRSUT.mrbpdomfd;
New_MRSUT_2.mrbpimpfd = New_MRSUT.mrbpimpfd;
New_MRSUT_2.mrbpdomva = New_MRSUT.mrbpdomva;
New_MRSUT_2.year = 2014;
New_MRSUT_2.meta = New_MRSUT.meta;
New_MRSUT_2.mrbpimp = New_MRSUT.mrbpimp;
New_MRSUT_2.mrbpdom = New_MRSUT.mrbpdom;

% 8.2 modisfying the supply table

New_MRSUT_2.mrsup = New_MRSUT.mrsup;

% 8.3 Collecting the total supply of each country

```

```
supply_steel = zeros(ncou,2);
product_steel = 104;
for i = 1:ncou
    supply_steel(i,1) = New_MRSUT.mrsup((i-1)*nprod + product_steel,(i-1)*nind+bof);
    supply_steel(i,2) = New_MRSUT.mrsup((i-1)*nprod + product_steel,(i-1)*nind+eaf);
end
% 8.4 The new steel shares
New_share = xlsread(FilenameIN2, 'New shares', 'J6:K54');

supply_steel_new = zeros(ncou,2);

for i = 1:ncou
    supply_steel_new(i,1) = New_share(i,1)*(supply_steel(i,1)+supply_steel(i,2));
    supply_steel_new(i,2) = New_share(i,2)*(supply_steel(i,1)+supply_steel(i,2));
end


for i =1:ncou
    New_MRSUT_2.mrsup((i-1)*nprod + product_steel,(i-1)*nind+bof) = supply_steel_new(i,1);
    New_MRSUT_2.mrsup((i-1)*nprod + product_steel,(i-1)*nind+eaf) = supply_steel_new(i,2);
end

% 8.5 now make new IOT for calculations using "PrepareMRSUTandCREATEixi.m"

%% 9. Scenario 3: BAT

% 9.1 All things connected to use-table are equal to the new ust-table
New_MRSUT_3.mrbpdom = New_MRSUT.mrbpdom;
New_MRSUT_3.mrbpdomfd = New_MRSUT.mrbpdomfd;
New_MRSUT_3.mrbpimpfd = New_MRSUT.mrbpimpfd;
New_MRSUT_3.mrbpdomva = New_MRSUT.mrbpdomva;
New_MRSUT_3.year = 2014;
New_MRSUT_3.meta = New_MRSUT.meta;
New_MRSUT_3.mrbpimp = New_MRSUT.mrbpimp;
New_MRSUT_3.mrbpdom = New_MRSUT.mrbpdom;

% 9.2 modisfying the supply table

New_MRSUT_3.mrsup = New_MRSUT.mrsup;

% supply to the steel technologies comes from product 104:
%'Basic iron and steel and of ferro-alloys and first products thereof'

```

```

% 9.3 Collecting the total supply of each country

supply_steel = zeros(ncou,2);
product_steel = 104;
for i = 1:ncou
    supply_steel(i,1) = New_MRSUT.mrsup((i-1)*nprod + product_steel,(i-1)*nind+bof);
    supply_steel(i,2) = New_MRSUT.mrsup((i-1)*nprod + product_steel,(i-1)*nind+eaf);
end

% 9.4 The new steel shares
New_share = xlsread(FilenameIN2, 'New shares', 'M6:N54');

supply_steel_new = zeros(ncou,2);

for i = 1:ncou
    supply_steel_new(i,1) = New_share(i,1)*(supply_steel(i,1)+supply_steel(i,2));
    supply_steel_new(i,2) = New_share(i,2)*(supply_steel(i,1)+supply_steel(i,2));
end


for i =1:ncou
    New_MRSUT_3.mrsup((i-1)*nprod + product_steel,(i-1)*nind+bof) = supply_steel_new(i
    ,1);
    New_MRSUT_3.mrsup((i-1)*nprod + product_steel,(i-1)*nind+eaf) = supply_steel_new(i
    ,2);
end
% 9.5 now make new IOT for calculations using "PrepareMRSUTandCREATEixi.m"

%% 10. Scenario 3: BAT China

% 10.1 All things connected to use-table are equal to the new ust-table
New_MRSUT_3c.mrbpdom = New_MRSUT.mrbpdom;
New_MRSUT_3c.mrbpdomfd = New_MRSUT.mrbpdomfd;
New_MRSUT_3c.mrbpimpfd = New_MRSUT.mrbpimpfd;
New_MRSUT_3c.mrbpdomva = New_MRSUT.mrbpdomva;
New_MRSUT_3c.year = 2014;
New_MRSUT_3c.meta = New_MRSUT.meta;
New_MRSUT_3c.mrbpimp = New_MRSUT.mrbpimp;
New_MRSUT_3c.mrbpdom = New_MRSUT.mrbpdom;

% 10.2 modisfying the supply table

New_MRSUT_3c.mrsup = New_MRSUT.mrsup;

```

```
% supply to the steel technologies comes from product 104:
%'Basic iron and steel and of ferro-alloys and first products thereof'


% 10.3 Collecting the total supply of each country

supply_steel = zeros(ncou,2);
product_steel = 104;
for i = 1:ncou
    supply_steel(i,1) = New_MRSUT.mrsup((i-1)*nprod + product_steel,(i-1)*nind+bof);
    supply_steel(i,2) = New_MRSUT.mrsup((i-1)*nprod + product_steel,(i-1)*nind+eaf);
end

% 10.4 The new steel shares
New_share = xlsread(FilenameIN2, 'New shares', 'Q6:R54');

supply_steel_new = zeros(ncou,2);

for i = 1:ncou
    supply_steel_new(i,1) = New_share(i,1)*(supply_steel(i,1)+supply_steel(i,2));
    supply_steel_new(i,2) = New_share(i,2)*(supply_steel(i,1)+supply_steel(i,2));
end


for i =1:ncou
    New_MRSUT_3c.mrsup((i-1)*nprod + product_steel,(i-1)*nind+bof) = supply_steel_new(i,1);
    New_MRSUT_3c.mrsup((i-1)*nprod + product_steel,(i-1)*nind+eaf) = supply_steel_new(i,2);
end


% 10.5 now make new IOT for calculations using "PrepareMRSUTandCREATEixi.m"

%% 11. Scenario 3: BAT India

% 11.1 All things connected to use-table are equal to the new ust-table
New_MRSUT_3i.mrbpdom = New_MRSUT.mrbpdom;
New_MRSUT_3i.mrbpdomfd = New_MRSUT.mrbpdomfd;
New_MRSUT_3i.mrbpimpfd = New_MRSUT.mrbpimpfd;
New_MRSUT_3i.mrbpdomva = New_MRSUT.mrbpdomva;
New_MRSUT_3i.year = 2014;
New_MRSUT_3i.meta = New_MRSUT.meta;
New_MRSUT_3i.mrbpimp = New_MRSUT.mrbpimp;
New_MRSUT_3i.mrbpdom = New_MRSUT.mrbpdom;
```

```

% 11.2 modisfying the supply table

New_MRSUT_3i.mrsup = New_MRSUT.mrsup;

% supply to the steel technologies comes from product 104:
%'Basic iron and steel and of ferro-alloys and first products thereof'


% 11.3 Collecting the total supply of each country

supply_steel = zeros(ncou,2);
product_steel = 104;
for i = 1:ncou
    supply_steel(i,1) = New_MRSUT.mrsup((i-1)*nprod + product_steel,(i-1)*nind+bof);
    supply_steel(i,2) = New_MRSUT.mrsup((i-1)*nprod + product_steel,(i-1)*nind+eaf);
end

% 11.4 The new steel shares
New_share = xlsread(FilenameIN2, 'New shares', 'T6:U54');

supply_steel_new = zeros(ncou,2);

for i = 1:ncou
    supply_steel_new(i,1) = New_share(i,1)*(supply_steel(i,1)+supply_steel(i,2));
    supply_steel_new(i,2) = New_share(i,2)*(supply_steel(i,1)+supply_steel(i,2));
end


for i =1:ncou
    New_MRSUT_3i.mrsup((i-1)*nprod + product_steel,(i-1)*nind+bof) = supply_steel_new(i,1);
    New_MRSUT_3i.mrsup((i-1)*nprod + product_steel,(i-1)*nind+eaf) = supply_steel_new(i,2);
end


% 11.5 now make new IOT for calculations using "PrepareMRSUTandCREATEixi.m"
```

A.4.5 CO_2 consumption-based emissions

```
%% Master project on Steel

load('IOT_2014_ixi.mat')
load('Steel_2011.mat')
filenameOUT = 'Master input from MatLab.xlsx';

ncou    = 49;  % number of countries
nind    = 163;    % number of industries
nstre   = IO.meta.Fdim;        % number of stressors
bof     = 72;                 % number of industry BF/BOF
eaf     = 73;                 % number of industry EAF
year    = IO.meta.years;

%% 1 Reformate IO.x and IO.A
% 1.2 Reformat output vector IO.x into two dimensions (ncou x nind)
xcou = zeros(ncou,nind);
for q= 1:ncou
    x_mid = IO.x(nind*(q-1)+1:q*nind);
    xcou(q,:) = x_mid';
end


% 1.2 Aggregate to country IO.A (coefficient) matrices in a 3 dimensional cube
Acou = zeros(nind,nind,ncou);
A_mid = zeros(1,nind*ncou);
A1 = zeros(nind, nind*ncou);
% first: get a two-dimensional matrix of size nind x (nind*ncou)
for i= 1:nind
    for r = 1:ncou
    A_mid = IO.A(nind*(r-1)+i,:);
    A1(i,:) = A1(i,:) + A_mid;
    end
end

% second: reformat that two dimensional matrix into the 3 dimensional cube
for p = 1:ncou
    Acou(: ,: , p) = A1(1:nind, (p-1)*nind +1:p*nind);
end

%% 2 Compare output shares of 72 / 73 with the external data on production technology shares

```

```
% 2.1 Top steel producing countries
totSteel  = zeros(ncou,1);
shareBOF    = zeros(ncou,1);
shareEAF    = zeros(ncou,1);
totBOF    = zeros(ncou,1);
totEAF    = zeros(ncou,1);
% 2.2 The output of steel from BF/BOF and EAF and total production from top
% steel producing countries:
for i = 1:ncou
    totSteel(i) = xcou(i,bof) + xcou(i,eaf);
    totBOF(i) = xcou(i,bof);
    totEAF(i) = xcou(i,eaf);
    shareBOF(i) = xcou(i,bof)./totSteel(i);
    shareEAF(i) = xcou(i,eaf)./totSteel(i);
end

shareBOF(isnan(shareBOF))=0;
shareEAF(isnan(shareEAF))=0;
%% 3. Energy carriers from A-matrix:


Industries = [20 21 22 23 25 56 69 94 96 134];
A_energy_carrier_BOF_2014 = zeros(length(Industries),ncou);
A_energy_carrier_EAF_2014 = zeros(length(Industries),ncou);
A_energy_carrier_BOF_2011 = zeros(length(Industries),ncou);
A_energy_carrier_EAF_2011 = zeros(length(Industries),ncou);

% 6.2 Collecting the production of electrisity from IO.A lines 96-107
for i = 1:ncou
     for p = 1:length(Industries)
          A_energy_carrier_BOF_2014(p,i) = Acou(Industries(p),72,i);
          A_energy_carrier_EAF_2014(p,i) = Acou(Industries(p),73,i);
     end
end


%% 4. New modified extensions
% 4.1 New extension based on the new use-table
filenameIN = 'Master input from MatLab.xlsx';
nstressor   = 260;              % number of new stressors

NewF = xlsread(filenameIN, 'NewExtension', 'C2:CV261');
F_new = extensions_industry;

% 4.2 insert the data to the correct location in the extension-matrix
```

```
k = 1;
for r = 1:ncou
    F_new(:,((r-1)*nind + 72)) = NewF(:,k);
    F_new(:,((r-1)*nind + 73)) = NewF(:,k+1);
    k = k+2;
end
IO.F = F_new;       % Create the F-matrix in the new IO-table


% 4.3 Find new stressors
stressor_BOF_new     = zeros(nstressor,ncou);
stressor_EAF_new     = zeros(nstressor,ncou);
stressors_new        = zeros(nstressor,2,ncou);


for p = 1:ncou
    e_i_new(: ,: , p) = IO.F(1:nstressor, (p-1)*nind +1:p*nind);
end

for i= 1:ncou
    stressor_BOF_new(:,i) = e_i_new(:,bof,i);
    stressor_EAF_new(:,i) = e_i_new(:,eaf,i);
end

for i = 1:ncou
    stressors_new(:,1,i) = e_i_new(:,72,i);
    stressors_new(:,2,i) = e_i_new(:,73,i);
end


% 4.4 The stressor matrix for the new extensions.
IO.S_new = zeros(size(IO.F));
stressor_per_output_BOF_new  = zeros(nstressor,ncou);
stressor_per_output_EAF_new  = zeros(nstressor,ncou);

IO.x_compareble = zeros(size(IO.x));
IO.x_compareble = IO.x/1000000; % make the x vector in million EURO


for i = 1:260
    IO.S_new(i,:) = IO.F(i,:)./transpose(IO.x_compareble);
end

IO.S_new(isnan(IO.S_new))=0;
IO.S_new(isinf(IO.S_new))=0;
```

```
S_new_all_scenarios = IO.S_new;
IO.S_new = S_new_all_scenarios; % stressor-matrix for all scenarios are equal

% 3-dimentional
for p = 1:49
    e_i_per_output_new(:  ,:  , p) = IO.S_new(1:nstressor, (p-1)*nind +1:p*nind);
end


for  i= 1:49
    stressor_per_output_BOF_new(:,i) = e_i_per_output_new(:,bof,i);
    stressor_per_output_EAF_new(:,i) = e_i_per_output_new(:,eaf,i);
end
stressor_per_output_BOF_new(isnan(stressor_per_output_BOF_new))=0;
stressor_per_output_EAF_new(isnan(stressor_per_output_EAF_new))=0;


% 4.5 The CO2-combustion new extension

CO2_BOF_new = stressor_per_output_BOF_new(196:260,:);
sum_CO2_BOF_new = sum(CO2_BOF_new,1);

CO2_EAF_new = stressor_per_output_EAF_new(196:260,:);
sum_CO2_EAF_new = sum(CO2_EAF_new,1);


%% 5 Emissions embodied in final consumption - modified for new and old use

I = eye(7987);
Y_mid1 = zeros(ncou*nind,ncou);      % old use
IO.Y_add = zeros(ncou*nind,ncou);    % new use


% 5.1 The Leontief inverse
L = (I-IO.A)^-1;     % old use
IO.L = (I-IO.A)^-1; % new use

% 5.2 Adding together the 7 final demand categories for each country:
for  i = 1:ncou
    Y_mid1(:,i) = IO.Y(:,(i-1)*7+1)+IO.Y(:,(i-1)*7+2)+IO.Y(:,(i-1)*7+3)+IO.Y(:,(i-1)*7+4)+IO.Y(:,(i-1)*7+5)+IO.Y(:,(i-1)*7+6)+IO.Y(:,(i-1)*7+7);     % old use
    IO.Y_add(:,i) = IO.Y(:,(i-1)*7+1)+IO.Y(:,(i-1)*7+2)+IO.Y(:,(i-1)*7+3)+IO.Y(:,(i-1)*7+4)+IO.Y(:,(i-1)*7+5)+IO.Y(:,(i-1)*7+6)+IO.Y(:,(i-1)*7+7);  % new use
end

```

```
% 5.3 The CO2-combustion emissions in all the countries and industries
F_fc3 = diag(IO.S(24,:))*L*Y_mid1; % old use

% 5.4 The CO2-combustion emissions
S_CO2_new = sum(IO.S_new(196:end,:),1); % sum the CO2-stressors:
S_diag_CO2_new = diag(S_CO2_new);       % diagonalise
F_fc3 = S_diag_CO2_new*IO.L*IO.Y_add;

% 5.5 The total consumption based CO2-combustion emissions for all the countries
Tot_P_cons = sum(F_fc3,1);

% 5.6 Total consumption based emissions from BF/BOF and EAF:
P_con_BOF = sum(F_fc3(bof:nind:end,:),1);
P_con_EAF = sum(F_fc3(eaf:nind:end,:),1);



% 5.7 Remake diag(IO.S(24,:)) to only include 72 and 73 and find CO2-emissions

% 5.7.1 Old use
S_diag_CO2 = diag(IO.S(24,:));
S_diag_72_73 = zeros(size(S_diag_CO2));

for i = bof:nind:ncou*nind
    S_diag_72_73(i,:) = S_diag_CO2(i,:);
    S_diag_72_73(i+1,:) = S_diag_CO2(i+1,:);
end
P_BOF_EAF = S_diag_72_73*L*Y_mid1;


% 5.7.2 New use and extension

S_diag_72_73_new = zeros(size(S_diag_CO2_new));

for i = bof:nind:ncou*nind
    S_diag_72_73_new(i,:) = S_diag_CO2_new(i,:);
    S_diag_72_73_new(i+1,:) = S_diag_CO2_new(i+1,:);
end

P_BOF_EAF = S_diag_72_73_new*IO.L*IO.Y_add;
P_BOF_EAF_tot = sum(P_BOF_EAF,1);

% 5.8 Domestic and imported CO2-emissions embodied in consumption
P_BOF_con = zeros(ncou,ncou);
P_EAF_con = zeros(ncou,ncou);
```

```
for i = 1:ncou
    P_BOF_con(i,:) = P_BOF_EAF(nind*(i-1)+72,:);
    P_EAF_con(i,:) = P_BOF_EAF(nind*(i-1)+73,:);
end

% 5.8.1 The domestic emissions
P_BOF_con_dom = zeros(ncou,1);
P_EAF_con_dom = zeros(ncou,1);
for i = 1:ncou
    for j = 1:ncou
        if i==j
            P_BOF_con_dom(i) = P_BOF_con(i,j);
            P_EAF_con_dom(i) = P_EAF_con(i,j);
        end
    end
end

% 5.8.2 The imported emissions
P_BOF_con_imp = transpose(sum(P_BOF_con,1))-P_BOF_con_dom;
P_EAF_con_imp = transpose(sum(P_EAF_con,1))-P_EAF_con_dom;



% 5.9 Breakdown of nine chosen countries
% 5.9.1 Emissions used domestically and emissions exported from China
P_BOF_China = P_BOF_EAF(4962,:);
P_EAF_China = P_BOF_EAF(4963,:);
P_tot_China = P_BOF_China+P_EAF_China;

% 5.9.2 Emissions used domestically and emissions exported from Japan
P_BOF_Japan = P_BOF_EAF(4799,:);
P_EAF_Japan = P_BOF_EAF(4800,:);
P_tot_Japan = P_BOF_Japan+P_EAF_Japan;

% 5.9.3 Emissions used domestically and emissions exported from US
P_BOF_US = P_BOF_EAF(4636,:);
P_EAF_US = P_BOF_EAF(4637,:);
P_tot_US = P_BOF_US+P_EAF_US;

% 5.9.4 Emissions used domestically and emissions exported from India
P_BOF_India = P_BOF_EAF(5614,:);
P_EAF_India = P_BOF_EAF(5615,:);
P_tot_India = P_BOF_India+P_EAF_India;

% 5.9.5 Emissions used domestically and emissions exported from South Korea (SK)
```

```
P_BOF_SK = P_BOF_EAF(5288,:);
P_EAF_SK = P_BOF_EAF(5289,:);
P_tot_SK = P_BOF_SK+P_EAF_SK;

% 5.9.6 Emissions used domestically and emissions exported from Russia
P_BOF_Russia = P_BOF_EAF(5940,:);
P_EAF_Russia = P_BOF_EAF(5941,:);
P_tot_Russia = P_BOF_Russia+P_EAF_Russia;

% 5.9.7 Emissions used domestically and emissions exported from Germany
P_BOF_Germany = P_BOF_EAF(887,:);
P_EAF_Germany = P_BOF_EAF(888,:);
P_tot_Germany = P_BOF_Germany+P_EAF_Germany;

% 5.9.8 Emissions used domestically and emissions exported from Brazil
P_BOF_Brazil = P_BOF_EAF(5451,:);
P_EAF_Brazil = P_BOF_EAF(5452,:);
P_tot_Brazil = P_BOF_Brazil+P_EAF_Brazil;

% 5.9.10 Emissions used domestically and emissions exported from EU28
P_BOF_EU28 = P_BOF_EAF(bof:nind:28*nind,:);
P_BOF_EU28 = sum(P_BOF_EU28,1);
P_EAF_EU28 = P_BOF_EAF(eaf:nind:28*nind,:);
P_EAF_EU28 = sum(P_EAF_EU28,1);
P_tot_EU28 = P_BOF_EU28+P_EAF_EU28;


%% 6 Consumption based emissions from selected stressors

% 6.1 stressor lines with values
stressor_line = [198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 214 215 217 218 222 223 224 225 226 227 228 229 230 231 232 233 234 235 237 238 239 241 244 245];

mid_mid = zeros(size(IO.A));
mid_mid1   = zeros(size(IO.A));
P_BOF_EAF_mid = zeros(ncou*nind,ncou);
P_BOF_EAF_stressor = zeros(length(stressor_line),ncou);
B = IO.L*IO.Y_add;
for i = 1:length(stressor_line)
    mid_mid(:,:) = diag(IO.S_new(stressor_line(i),:));      % make the diagonal for the selected stressor
    mid_mid1(bof:nind:ncou*nind,:) = mid_mid(bof:nind:ncou*nind,:);
    mid_mid1(eaf:nind:ncou*nind,:) = mid_mid(eaf:nind:ncou*nind,:);
    P_BOF_EAF_mid(:,:) = mid_mid1(:,:)*B(:,:); % calculate for one stressor
```

```
    P_BOF_EAF_stressor(i,:) = sum(P_BOF_EAF_mid,1);          % add together all stressors
    i
end


%% 7 Modifying the y-matrix to find the downstream industires with emissions embodied in steel
% 7.1 The CO2-emissions embodied in the different industries due to emissions from steel

% 7.1.1 old use
Pollution = zeros(ncou*nind,ncou);
P_ind_72_73 = zeros(nind,ncou);
y_select = zeros(size(Y_mid1));
B = S_diag_72_73*L;
for i = 1:nind
    y_select(i:nind:end,:) = Y_mid1(i:nind:end,:);
    Pollution = B*y_select;
    P_ind_72_73(i,:) = sum(Pollution,1);
    y_select = zeros(size(Y_mid1));
end

% 7.1.2 new use
y_select = zeros(size(IO.Y_add));
Pollution = zeros(ncou*nind,ncou);
P_ind_72_73_new = zeros(nind,ncou);
B = S_diag_72_73_new*IO.L;
for i = 1:nind
    y_select(i:nind:end,:) = IO.Y_add(i:nind:end,:);
    Pollution(:,:)   = B(:,:)*y_select(:,:);
    P_ind_72_73_new(i,:) = sum(Pollution,1);
    y_select = zeros(size(IO.Y_add));
end

IO.P_ind_72_73_new = P_ind_72_73_new; % Save in struct

% 7.2 The total CO2-emission embodied in consumption from steel
P_ind_total = sum(P_ind_72_73,1);            % old use
P_ind_total = sum(IO.P_ind_72_73_new,1);     % new use

% 7.3 The CO2-emission from steel embodied in consumption shares
P_ind_share = zeros(nind,ncou);

% 7.3.1 old use
for i = 1:nind
    P_ind_share(i,:) = P_ind(i,:)./P_ind_total;
```

```
end

% 7.3.2 new use
for i = 1:nind
    P_ind_share(i,:) = IO.P_ind_72_73_new(i,:)./P_ind_total;
end


% 7.4 The CO2-emissions embodied in the different industries due to total
% emissions form all industries


% 7.4.1 old use
P_ind_all_industries = zeros(nind,ncou);
Pollution = zeros(ncou*nind,ncou);
B1 = S_diag_CO2*L;
for i = 1:nind
    y_select(i:nind:end,:) = Y_mid1(i:nind:end,:);
    Pollution = B1*y_select;
    P_ind_all_industries(i,:) = sum(Pollution,1);
    y_select = zeros(size(Y_mid1));
end

% 7.4.2 new use
y_select = zeros(size(IO.Y_add)); % New use
Pollution = zeros(ncou*nind,ncou);
P_ind_all_industries = zeros(nind,ncou);
B1 = S_diag_CO2_new*IO.L;
for i = 1:nind
    y_select(i:nind:end,:) = IO.Y_add(i:nind:end,:);
    Pollution(:,:) = B1(:,:)*y_select(:,:);
    P_ind_all_industries(i,:) = sum(Pollution,1);
    y_select = zeros(size(IO.Y_add));
    i
end

IO.P_ind_all_industries = P_ind_all_industries; % save in struct

%% 8. Looking at the BF/BOF and EAF
% 8.1 BF/BOF
% 8.1.1 old use

y_select_BOF = zeros(size(Y_mid1));
y_select_BOF(bof:nind:end,:) = Y_mid1(bof:nind:end,:);
Pollution_BOF = S_diag_CO2*L*y_select_BOF;
```

```
Pol_BOF = zeros(nind,ncou);

for i= 1:nind
    for r = 1:ncou
        indx_A =nind*(r-1)+i;
        mid = Pollution_BOF(indx_A,:);
        Pol_BOF(i,:) = Pol_BOF(i,:) + mid;
    end
end

% 8.1.2 new use
y_select_BOF = zeros(size(IO.Y_add));
y_select_BOF(bof:nind:end,:) = IO.Y_add(bof:nind:end,:);
Pollution_BOF = S_diag_CO2_new*IO.L*y_select_BOF;

Pol_BOF = zeros(nind,ncou);
for i= 1:nind
    for r = 1:ncou
        indx_A =nind*(r-1)+i;
        mid = Pollution_BOF(indx_A,:);
        Pol_BOF(i,:) = Pol_BOF(i,:) + mid;
    end
end

% 8.2  EAF
% 8.2.1 old use
y_select_EAF = zeros(size(Y_mid1));
y_select_EAF(bof:nind:end,:) = Y_mid1(bof:nind:end,:);
Pollution_EAF = S_diag_CO2*L*y_select_EAF;
Pol_EAF = zeros(nind,ncou);

for i= 1:nind
    for r = 1:ncou
        indx_A =nind*(r-1)+i;
        mid = Pollution_EAF(indx_A,:);
        Pol_EAF(i,:) = Pol_EAF(i,:) + mid;
    end
end



% 8.2.2 new use
y_select_EAF = zeros(size(IO.Y_add));
y_select_EAF(eaf:nind:end,:) = IO.Y_add(eaf:nind:end,:);
Pollution_EAF = S_diag_CO2_new*IO.L*y_select_EAF;
```

```


Pol_EAF = zeros(nind,ncou);
for i= 1:nind
    for r = 1:ncou
        indx_A =nind*(r-1)+i;
        mid = Pollution_EAF(indx_A,:);
        Pol_EAF(i,:) = Pol_EAF(i,:) + mid;
    end
end


%% 9 Output shares of 72 / 73 for all EXIOBASE countries for 2011 and 2014

output_total  = zeros(ncou,1);
output_BOF =  zeros(ncou,1);
output_EAF =  zeros(ncou,1);
shareBOF    = zeros(ncou,1);
shareEAF    = zeros(ncou,1);
totSteel1   = zeros(1,ncou);

% 9.1 The output of steel from BF/BOF and EAF and total production:
for i = 1:ncou
   output_total(i) = xcou(i,72) + xcou(i,73);
   output_BOF(i) = xcou(i,72);
   output_EAF(i) = xcou(i,73);
   shareBOF(i) = xcou(i,72)./output_total(i);
   shareEAF(i) = xcou(i,73)./output_total(i);
end

% 9.2 Total output of steel in the world:
for i = 1:ncou
   totSteel1(i) = xcou(i,72) + xcou(i,73);
end
totSteel = sum(totSteel1,2);

% 9.3 Steel production for all countries
Steel = zeros(ncou,1);
for i = 1:ncou
   Steel(i) = xcou(i,72) + xcou(i,73);
end

% 9.4 After re-allocation

% 9.4.1 total output from steel
```

```
BOF_output = IO.x_compareble(bof:nind:end,:);
EAF_output = IO.x_compareble(eaf:nind:end,:);

totSteel = BOF_output + EAF_output;

% 9.4.5 share of the technologies
shareBOF = BOF_output./totSteel;
shareEAF = EAF_output./totSteel;
```