

DISCUSSION PAPER

Decarbonizing the East Asian Steel Industry in 2050: **An analysis performed with FTT(Future Technology Transformation)-Steel model**

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Decarbonizing the East Asian steel industry in 2050:

An analysis performed with FTT(Future Technology Transformation)-Steel model.

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Abstract:

In this paper the Chinese, Japanese, Korean, and Taiwanese iron and steel industries will be exposed to varying carbon taxes of 50, 100, and 200 US\$ per tonne carbon. We will see how much stimulate the speed of low carbon technological innovation and how much impact on the production of steel industry and whole economy by connecting FTT to E3ME model by 2050 in each carbon tax rate. Imposing an increasing carbon tax of 200 US\$ will lead to a 75% emission reduction for China, Japan, Korea and Taiwan combined. The greatest reduction occurs in China, where Scrap-EAF now gains substantial market shares. Regulatory policies on the fossil-based BF-BOF route leads to an overall emission reduction of 57%. Under those conditions fuel-switching towards biomass occurs and Hydrogen Flash Smelt (HFS) will be incentivised. Subsidizing policies have little effect since the greatest cost component is the fuel and material consumption.

Key Words:

East Asia, Steel Industry, Carbon Tax, Low Carbon Technologies,

1. Introduction

The focus of climate mitigation is naturally on the heavy emitting sectors, such as the power, transport and industry sectors. The industrial sector is a broad term that consists of many different types of industry, e.g. the cement, paper and pulp, (petro-)chemical, and steel industry. The latter was responsible for 31% of all direct industrial emissions [1]. Steel production from virgin materials is a carbon intensive process ($1.5 - 3.3 \text{ tCO}_2\text{-eq.} / \text{tcs}$ [2]), because carbon containing materials are necessary to reduce iron ore to iron. It is also an energy intensive process ($19.8\text{--}31.2 \text{ GJ} / \text{tcs}$ [2]). For these reasons, mainly coal resources (either directly or in the form of coke) are used, both as a reducing agent and as a combustible energy source.

In 2015 the manufacturing and construction industry in China, Japan, South Korea, and Taiwan (CJKT) were together accountable for 1893 Mt of $\text{CO}_2\text{-eq.}$ emitted to the atmosphere, of which 1652 Mt, 152 Mt, 89 Mt $\text{CO}_2\text{-eq.}$ due to China and Taiwan combined, Japan and South Korea respectively and together they constitute 74% of the total emissions of the steel industry in the world [3]. Of these emissions, 40~50% of the manufacturing industry and 10~20% of total emission in CJKT were attributable to the iron and steel industry.

The introduction and diffusion of novel, low carbon intensive technologies could lead to large emission reductions of the steel industry, because evolution of low carbon steel technologies could reduce CO_2 emissions. In order to be able to predict how innovation will take place in the future a model is needed. By using a bottom-up, non-equilibrium, evolutionary, future technological transformations (FTT) can be modelled given the sectoral-specific conditions [4]. FTT was designed for that purpose and previously the power [5], road transport [6], and residential heating sectors [7] were modelled. This model applies Schumpeterian economics to model incremental and radical innovation [8].

In this model 26 integrated steelmaking technologies were investigated, in 59 regions from the period 2015 to 2050. At the start of modelling, the conventional Blast Furnace-Blast Oxygen Furnace (BF-BOF) route and the Scrap-EAF routes had the greatest markets shares. The model also includes radical new technologies that are currently still in research phase, such as Hydrogen Flash Smelt (HFS) coupled to EAF and Molten Oxide Electrolysis (MOE). To the technologies where it applies to, bio-based and CCS options were also added. In brief, future technological transformations can be modelled given the sectoral-specific conditions. Technological diffusion is calculated according to the levelized cost of steel production (LCOS) and how it changes over time. The technological changes lead to differences in annual emissions, sectoral investments, and material consumption. The mathematical framework is elaborately described in more detail by Mercure [5].

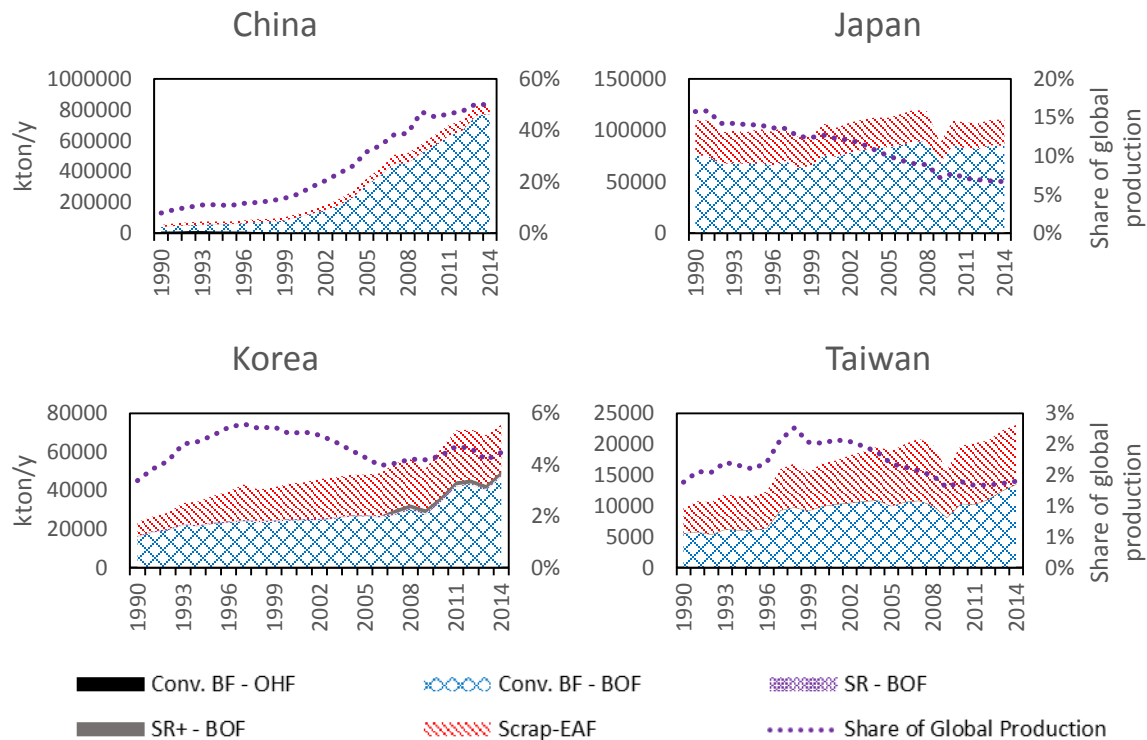
In this study the CJKT iron and steel industries will be exposed to a low, medium, high carbon tax. Based on these policy scenarios, we evaluated their effects on the diffusion of technologies within the iron and steel sector for the CJKT domain. Based on the technology mixtures, the CO_2 emissions were estimated. Ultimately, it is the goal of this research to provide policymakers in China, Japan, Korea, and Taiwan with valuable insights on how low carbon policies such as carbon taxes affect technological diffusion until 2050 in the iron and steel industry.

To evaluate this research goal, it is imperative to consider the current status of the countries' economies and steel industries. The country profiles in regard to the steel sector will be described in section 2. In section 3, the methods are presented; First, by elaborating the scope of this in regard to integrated steel production technologies; Second, by describing how innovation was simulated in this work; And third, by presenting the low carbon policy scenarios used for simulation. In section 4, the results are displayed and discussed as they are presented. Finally, in section 5, we briefly summarise the main conclusions.

2. Country profiles of East Asia

Of all steel produced, the 62% originates from East Asian [9]. China, Japan, Korea, and Taiwan are the 1st, 2nd, 6th, and 12th largest steel producers in the world. For that reason, this dissertation will focus on these countries. China produced roughly 823 Mt of crude steel in 2014. In the same year, Japan, South Korea, and Taiwan produced 111, 72, and 23 Mt of crude steel respectively [9], see also figure 1. China's total steel output is slightly greater than that of the rest of the world (RoW) combined, but has not always been the case. Steel production in China increased tremendously since 1990, by 1385%. In 1990, Japan was the world's largest steel producer with an output of 110 Mt of crude steel while China produced half of that [9]. The Chinese growth can be explained by its growth in GDP over the same period, whereas Japan, Korea, and Taiwan have reached economic maturity well before China has [10]. During the economic expansion of China, the demand for steel rose, as more cars were purchased and more buildings were built, so the steel industry grew as a result of that [11].

Figure 1 Historical production by technology (left axis), and the share of the total crude steel production compared to the total global production (right axis).



The bulk of all steel production in 2017 occurred in integrated steelmills. These mills consist of blast furnace (BF) units to reduce the iron ore to pig iron, which is subsequently refined in the basic oxygen furnace (BOF) to crude steel [9]. Virtually all other steel was produced in an electric arc furnace (EAF) via two primary routes [9]. One route is connected to the direct reduction (DR) technology, of which two types exist: gas-based and the coal-based DR. Within a DR plant the fossil fuel (natural gas or coal) is reformed to produce a highly reductive syngas. Iron ore agglomerates are fed into the DR plant and reduced to iron without melting it [12]. The intermediate iron product is then refined in the EAF. The other EAF route does not consume virgin materials, but steel scrap instead.

The market share of the Scrap-EAF route declined slightly in China and that can be explained due to two factors. First, the steel production surged the last two decades. Second, the availability of scrap was and is limited in China. According the World Steel Association, the import of scrap does not contribute much for the scrap availability in China [9]. The outdated OHF steelmaking process has been discontinued around the year 2000. For Japan, Korea, and Taiwan the shares of EAF is greater and that is due to scrap being relatively more abundantly available compared to the total production. Korea also has integrated steelworks that utilise the COREX and FINEX processes to reduce iron ore, coupled to the BOF. Both are smelt reduction (SR) technologies with the distinction that FINEX is more advanced (SR+).

2.1 China & Taiwan

China. Before World War II, the Chinese steel industry was of insignificant size. However, afterwards the government began to develop its outdated industries, such as the iron and steel industry. Since the 90's the Chinese crude steel output grew very rapidly. From 1996 to 2003, steel production doubled, from to ~100 Mt to ~200 Mt. It doubled again to ~400 Mt in 2006, and again to ~800 Mt in 2014 [9]. This growth can be explained by the economic growth [10] and government incentives that increased steel demand [13]. Since then steel production stagnated due to a slowdown in steel demand.

The apparent steel use in China grew considerably recent years and this was mainly driven by the government's stimulus package in 2017 [9]. In the near future it is expected to stagnate due to a slowdown in steel demand of the industry [14]. For the mid-term future, steel demand in China might decline because of a decreasing producible population [15], a decline in investment growth due to an increase in credit debt [16], and a decline caused by improvements of the steel quality.

The Chinese steel industry is under pressure due to a domestic overcapacity [17]. China had a production capacity greater than 1.5 Gt of crude steel in 2015 [13]. With a steel output of roughly 803 Mt of crude steel it means that the utilisation factor of the integrated steelworks was approximately 53%. The government of China decided to decrease the production capacity in the coming years. Up to 2020 it wants to reduce its capacity by 10% [13]. It will do so, by focusing on closing down small inefficient plants and by merging steel companies [18].

According to the Chinese NDC, the country should lower its energy intensity per unit of GDP by 40-45% by 2020 compared to 2005. It will reach peak emissions and initiate reduction by 2030. The country will invest in research and development (R&D) on carbon capture and storage (CCS). Another important statement from the NDC is China's pledge in employing a national emission trading scheme (ETS) [19]. The ETS system should be implemented in a timeframe of 2 – 3 years [20], which then acts as a market pull mechanism to increase the production costs of emission intensive integrated steelworks and thereby making lower emission intensive technologies more competitive.

In addition to the Chinese NDC, the "Adjustment and Upgrading Plan of the Steel Industry" was enacted. Its main goal is to implement green upgrading, circular economy, promote green consumption, and decrease the energy intensity up to 2020.

Taiwan. Whereas the world committed to keep global warming well below 2 degrees Celsius during the 2015 PA, Taiwan was left out due to political disputes. Yet, it unilaterally announced its "*Greenhouse Gas Reduction and Management Act*" [21]. The Taiwanese GHG target is to reduce emissions by 50% in 2030 compared to BAU emissions. No specific actions were taken against GHG emission reductions for the iron and steel industry other than reducing the emission intensity without a quantitative target.

2.2. Japan

The history of iron and steel industry in Japan can be termed the history of the development of capitalism in Japan. In 1866, the government established iron works at Yokosuka and Yokohama [22]. In early time, the iron works was directly under government control to the necessity of securing sufficiently military power. It was then recognised that the establishment of a modern large-scale iron manufacturing industry was of utmost importance in order to systemise and organise these technical successes into a modern military force with support of a capitalistic economy in its background.

Currently, the steel industry has become one of the major industries in Japan, accounting for 7.2% (6.4 trillion yen) of the manufacturing GDP in 2012. As of 2015, there are 4 domestic blast furnace companies with 28 blast furnace steelworks, 10 special steel industry companies, and 32 ordinary steel blast furnaces. The crude steel production is about 110 million tons per year [9]. Steel is currently one of the major export items in Japan and the proportion of total exports is increasing due to the expansion of exports to Japanese automobile assembly base countries and exporting about 40 percent of crude steel production [23]. According to the Japan Iron and Steel Federation (JISF), in 2016, crude steel output in Japan continued to decline early in the year as domestic demand was weak. But output slow began to recover in the spring along with a rebound in demand in the construction and automobile industries [24]

The Japanese steel industry is constantly developing technologies to supply high-grade steel that can meet the diversifying and exacting requirements of companies that use steel products. At the same time, steelmakers are achieving more productivity gains in all manufacturing processes. Fiscal 2008 was the beginning of a project called COURSE50 (CO₂ Ultimate Reduction in Steelmaking Process by Innovative technology for cool Earth 50). A closer look into the COURSE50 programme reveals that it aims to develop less carbon intensive steelmaking technologies to meet a GHG emission reduction target of 80% by 2050 [25]. This programme evaluates technologies that incorporate hydrogen or biomass, CCS, and direct electrowinning. The latter involves electrolysis of the iron ore [26]. These technologies are expected to be introduced commercially by 2030 and increase in market share from then on.

Japan has formulated an NDC target of 26% GHG emission reduction by 2030 compared to 2013 [27]. In its NDC it has explicitly formulated targets for the iron and steel industry:

- Efficiency improvement of electricity-consuming facilities
- More chemical recycling of waste plastic at steel plants
- Introduction of next-generation coke making
- Improvement of power generation efficiency process (SCOPE21)
- Enhanced energy efficiency and conservation facilities
- Introduction of innovative ironmaking process (Ferro Coke)
- Introduction of environmentally harmonized steelmaking process (COURSE50)

In response to the Global Warming Countermeasures Japanese Cabinet approved in May 2016, the Japanese steel industry reaffirmed that it will steadily implement the Commitment to a Low Carbon Society, and is already engaged in efforts, centering on the JISF [28]. As one way to flight global warming, the Japanese steel industry is going ahead with the 'Commitment to a Low Carbon Society' as a new voluntary initiative that started in fiscal 2013. There are four central components: eco-process, eco-product, eco-solution and the development of innovative technologies. One goal is to further improve the steel industry's energy efficiency, which is the highest in the world. Another goal

is to contribute to the fight against global warming by increasing the use of Japan's outstanding steel products and energy conservation technologies around the world [24].

2.3. Korea

The Korean government initiated the steel industry's exponential growth in the 1960's and this resulted in ranking 6th in terms of total crude steel production since 1995. This growth went hand-in-hand with Korea's economic growth [10]. However, the Korean economy is sluggish at the moment, resulting in a decline in steel demand of shipbuilders and car manufacturers [29].

The Korean government has set GHG emission reduction targets of 30% below BAU by 2020 and 37% below BAU by 2030, as presented in its NDC. The national target for steel industry is an emission reduction of 11.1% compared to BAU in 2030. On the 1st of January in 2015, the Korean ETS went in force and the iron and steel industry is not exempted from it [30]. The ETS is also part of Korea's NDC to reduce its GHG emission, which they have set as a voluntary target after the UNFCCC conference of parties (COP) at Copenhagen in 2009. After the COP in Paris in 2015, this became their NDC [31].

The largest Korean steel company, POSCO, has set its own GHG reduction target. It aims to reduce the emission intensity of steel production by 9% by 2020 compared to the average level of 2007-2009. POSCO intends on achieving that target by reducing coal consumption, improving energy efficiency and developing innovative low carbon technologies. Their focus has shifted towards hydrogen-based steelmaking, which would be essentially emissions when only direct CO₂ emissions are considered [32].

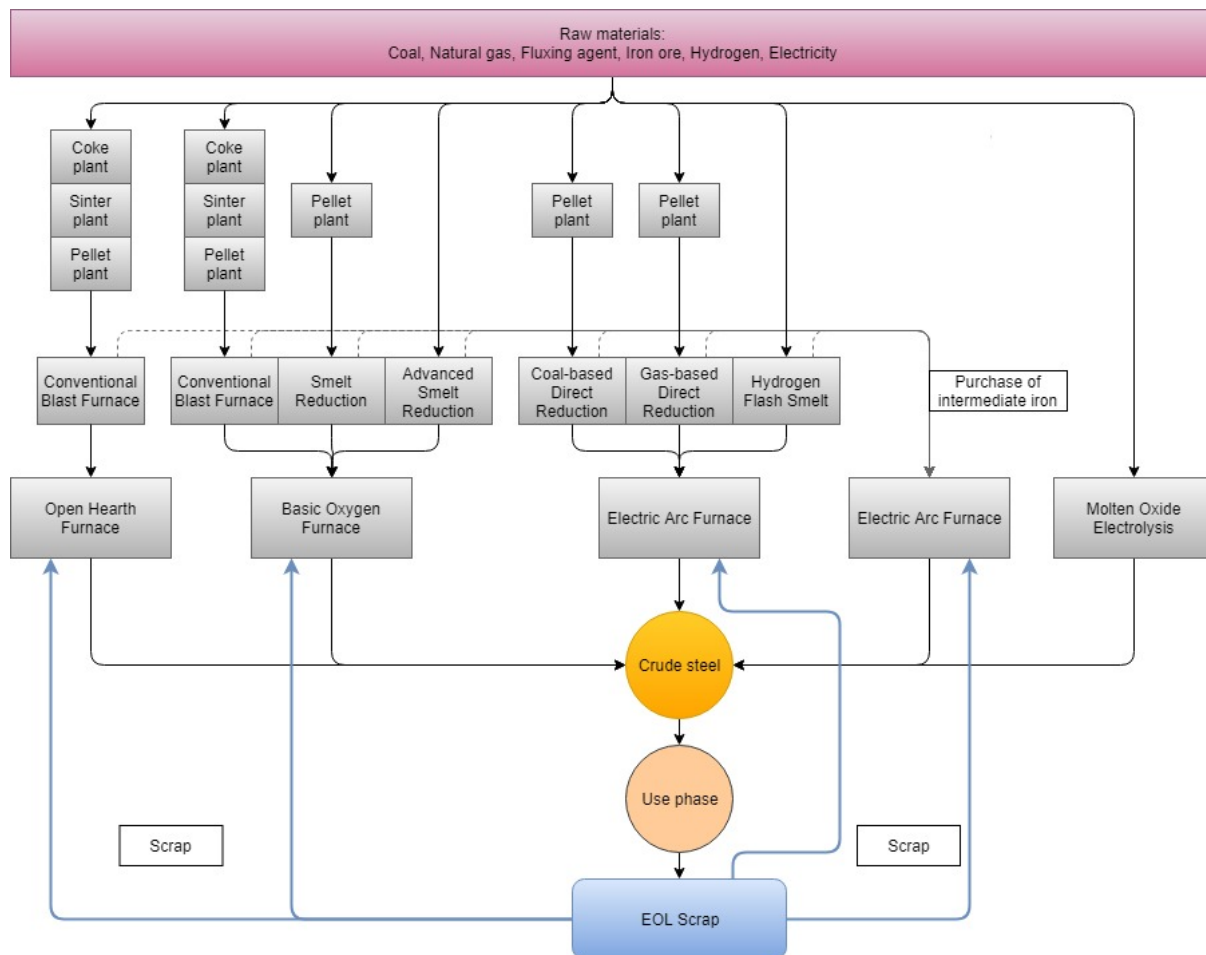
Korea's proximity to China also poses another issue. Many of the Chinese industry is located along its coast and Korea is located downwind of the Chinese emissions. Especially PM_{2.5} is a problem for Korea and therefore the Korean focus is not just on reducing CO₂ emissions, but mainly PM_{2.5} emissions. For this reason, POSCO developed the FINEX process (SR+ technology), which contributes considerably less to PM_{2.5} formation. Furthermore, FINEX does not require precursor plants to pre-process the raw materials [33].

3. Methods and Materials

3.1 Integrated steelmaking technologies

A literature review of research papers, policy documents, and institutional reports were consulted to setup the technologies implemented in FTT:Steel. In this study, we only considered the complete pathways from raw materials and scrap to crude steel. The finishing processes of crude steel were excluded, since these processes do not consume raw materials and the direct CO₂ emissions are lower than those of the other processes [34]. An overview of all integrated steelmaking routes are illustrated in figure 5 and a more elaborate description of the technologies can be found in Appendix.

Figure 2 The varying routes towards crude steel production.



Precursor plants. In some cases the raw materials require pre-processing. In a coke plant, hard coal is converted to coke to serve as a better reducing agent [35]. Most ironmaking processes require high quality iron ore, called lump ore, which is becoming increasingly rare. To circumvent using solely lump ore, many integrated steel plants have sinter plants or pelletizing plants available onsite to produce iron ore agglomerates, which have a higher porosity to increase the rate of reduction from iron oxides to metallic iron [36]. Some integrated steelworks have an onsite lime kiln to produce burnt lime with limestone as input. This is used as fluxing agent in the iron ore reduction process to get rid of the impurities. However, the overall limestone/lime use is low, so this process does not bare the largest portion of the costs associated with steel production. A similar argument applies for an oxygen plant [37].

Ironmaking technologies. The conventional blast furnace (Conv. BF) is currently the most commonly used process to reduce iron oxides to metallic iron [9]. Coke and iron ore agglomerates are required as feed materials [38]. Other currently used process are direct reduction, by either reforming natural gas (DR-gas) or coal (DR-coal), which does not require coke but it does require iron ore agglomerates [12,34]. Smelt reduction (SR) has recently gained a market share in the iron and steel sector and like the DR processes it only requires agglomeration of iron ore to some degree [39].

Many research and development programs around the world have put effort into several ironmaking innovations (e.g. [25,40]). The blast furnace coupled to a top gas recovery unit (BF TGR) should reduce the need for raw materials as energy is recycled to some degree [41]. Like the Conv. BF it requires precursor plants. An advanced version of the SR technology group (SR+) does not require any precursor plants as it can use coal and iron ore of any quality as feed material [33,42]. To curb emissions, efforts have been made to develop a process that uses hydrogen as the reducing agent

instead of carbon. The most promising technology is named hydrogen flash smelt (HFS). Neither HFS requires precursor steps [43–46].

Steelmaking technologies. The oldest technology currently still in use, but decreasing in market share, is the Open Hearth Furnace (OHF) [9]. Over time the OHF got replaced by the basic oxygen furnace (BOF) due to the former being a batch process [36]. The OHF and BOF require fossils to remove impurities and reduce the carbon content from the intermediate iron products of the ironmaking steps. Both the OHF and BOF are usually connected to the Conv. BF, but these steelmaking furnaces can also be connected to the SR, SR+, and BF TGR ironmaking technologies. In this study those connections to the OHF process were omitted due to OHF disappearing in market share. Currently, all remaining steel is produced in electric arc furnaces (EAF) [9]. As its name suggest, EAF consumes mainly electricity [38]. The last steelmaking technology included in this study is the molten oxide electrolysis (MOE). This novel technology electrolyses iron oxide into metallic iron which is of crude steel quality [26,47,48]. Without taking into account the emissions due to electricity generation, MOE does not emit CO₂ during its production process.

Variations. While figure 5 shows the main integrated steelmaking technologies, it excludes the use of biomass, CCS/CCU, and a combination of both. Where applicable these were implemented for certain technologies. For example, the Conv. BF-BOF route can consume biomass in the form of charcoal, partly as reductant and as a fuel source [49]. Also CCS can be implemented to Conv. BF-BOF plants, and a combination of biomass and CCS as well. Table x shows all the technologies and variations thereof. Table 1 shows the variations for each integrated steelmaking route.

Table 1 All technologies included in FTT:Steel and their variations.

<i>Ironmaking technology</i>	<i>Steelmaking technology</i>	<i>Integrated steelmaking designation</i>	<i># of variations</i>
Conv. BF	OHF	Conv. BF-OHF	1 (D)
Conv. BF	BOF	Conv. BF-BOF	4 (D,BB,CCS,CCSBB)
BF TGR	BOF	BF TGR-BOF	2 (CCS, CCSBB)
DRI (gas)	EAF	DRI (gas) -EAF	4 (D,BB,CCS,CCSBB)
DRI (coal)	EAF	DRI (coal) -EAF	4 (D,BB,CCS,CCSBB)
SRI	BOF	SRI-BOF	4 (D,BB,CCS,CCSBB)
SRI+	BOF	SRI+-BOF	4 (D,BB,CCS,CCSBB)
HFS	EAF	HFS-EAF	1 (D)
-	MOE	MOE	1 (D)
-	EAF	Scrap-EAF	1 (D)
<i>Total No. of technologies in FTT:Steel</i>			26

Note: D = Default, BB = Biobased based, CCS = Carbon Capture and Storage / Utilisation, CCSBB = Carbon Capture and Storage / Utilisation in combination with Biobased materials.

Table 2 shows the costs (CAPEX and OPEX), emission factors (EF), and energy intensities (EI) for the production of 1 ton of crude steel (tcs). Here, a scrap input of 15% for the primary production technologies and 100% for the secondary production technology was estimated. All biobased technologies show high costs due to the expected high costs of charcoal or biogas. All CSS/CCU options show slightly higher costs than the default version of the steelmaking route. In this study, the capital expenditure (CAPEX) of the CCS/CCU options was increased by 50 \$₂₀₀₈/tCO_{2,avoided}, and the operating expenses (OPEX) was increased by 5 \$₂₀₀₈/tCO_{2,avoided}. For the biobased options, only the material input changed, which increased the total cost of material consumption and CO₂ emissions. Note that coke production cannot occur fully biobased [49].

Table 2 CAPEX, OPEX, emission factors, and energy intensities, based on own estimates following the data of several sources..

Technologies	CAPEX	OPEX	EF*	EI	Material / Energy costs**			
	\$ ₂₀₀₈ /tcs cap.	\$ ₂₀₀₈ /tcs prod.	tCO ₂ / tcs	GJ / tcs	\$ ₂₀₀₈ /tcs prod.			
					C	J	K	T
Conv. BF – OHF	490 [36,38,50]	60 [36,38,50]	2.104 (2.18-2.30) [Calculation]	22.74 [Calculation]	213.7 [Calc.]	264.4 [Calc.]	241.2 [Calc.]	281.5 [Calc.]
Conv. BF – BOF	460 [36,38,50]	50 [36,38,50]	1.783 (1.87-1.98) [Calculation]	20.03 [Calculation]	209.3 [Calc.]	253 [Calc.]	234.2 [Calc.]	264.3 [Calc.]
BF TGR – BOF	632 [38,41]	51 [38,41]	0.3569 (0.53-0.76) [Calculation]	19.35 [Calculation]	223.8 [Calc.]	282.1 [Calc.]	260.7 [Calc.]	280.7 [Calc.]
DR-gas – EAF	450 [36,38]	55 [36,38]	0.691 (1.13-1.71) [Calculation]	14.98 [Calculation]	305 [Calc.]	445.5 [Calc.]	440.2 [Calc.]	386.1 [Calc.]
DR-coal – EAF	450 [36,38]	55 [36,38]	2.677 (3.11-3.67) [Calculation]	31.99 [Calculation]	277.6 [Calc.]	413.8 [Calc.]	343.6 [Calc.]	392.8 [Calc.]
SR – BOF	372 [36,39,51]	39 [36,39,51]	2.481 (2.54-2.61) [Calculation]	26.56 [Calculation]	201.7 [Calc.]	270.1 [Calc.]	245.6 [Calc.]	296.5 [Calc.]
SR+ - BOF	285 [33,52]	35 [33,52]	1.235 (1.32-1.43) [Calculation]	13.82 [Calculation]	195.9 [Calc.]	239.8 [Calc.]	220 [Calc.]	244.5 [Calc.]
HFS – EAF	367 [38,44,45]	57 [38,44,45]	0.0138 (0.54-1.23) [Calculation]	16.96 [Calculation]	413.5 [Calc.]	498.7 [Calc.]	442.5 [Calc.]	430.4 [Calc.]
MOE	4000 [53]	37 [53]	0.0058 (5.13-11.83) [Calculation]	39.7 [Calculation]	539 [Calc.]	1528 [Calc.]	971.1 [Calc.]	678.4 [Calc.]
Scrap-EAF	81 [38]	37 [38]	0.0138 (0.40-0.91) [Calculation]	3.25 [Calculation]	279.5 [Calc.]	293.8 [Calc.]	260.7 [Calc.]	303.5 [Calc.]

Note: The estimates of the emission factors and energy intensities were based on 15% scrap consumption per tcs for the primary steelmaking routes, with the exception of MOE which produces crude steel directly from iron ore. The emission factors only entail direct emissions. In brackets the indirect emissions due to electricity consumption are presented.

**: For the calculation of indirect CO₂ emissions due to electricity consumption, we used the emission factors of CJKT and reported the min-max ranges. Emission factors due to electricity consumption were taken from [54].*

*** : Material costs are presented for each of the East Asian countries of interest (C=China, J=Japan, K=Korea, T=Taiwan).*

The CAPEX of the SR+ - BOF, HFS-EAF and Scrap-EAF routes were found to be lower than those of the other technologies. The main reason is that neither of these require installed capacity of precursor plants for raw material processing. MOE is an exception to this rule. Not only is MOE expensive in terms of CAPEX, but also in terms of material costs. It consumes a lot of electrical energy, however, bear in mind that regional prices vary. The costs in table 2 were calculated by using average prices. HFS-EAF, MOE, and Scrap-EAF are the only non-carbothermic processes and therefore have the lowest emission factors. Furthermore, since Scrap-EAF does not require reduction of iron ore, it has a much lower energy intensity compared to the other technology pathways.

3.2 FTT Methodology

In this model, the diffusion of integrated steelmaking technologies was investigated, in 59 regions from the period 2015 to 2050. To achieve this, we used a mathematical framework described in Mercure [5] and Mercure et al. [55], previously applied to the diffusion of power generation, road transport, and residential heating technologies. The mathematical framework is briefly repeated here, see Appendix for a more detailed description. Decision making behind the diffusion process is assumed to be cost-based. Within the mathematical framework, the discounted levelized cost for the production of 1 tonne of crude steel (*LCOS*) is calculated according to equation 1. It constitutes the break-even cost of crude steel production, which is compared between competing technologies, guiding investment decisions by heterogeneous agents.

$$\text{Eq.1 } LCOS = \frac{\sum_0^{\tau} \frac{IC/CF + OM + FC + CO_2C}{(1+r)^t}}{\sum_0^{\tau} \frac{1}{(1+r)^t}}$$

where *IC* is the investment cost, and it is divided by the capacity factor (*CF*) and the lead time, *OM* are the operation and maintenance costs, *FC* are the costs of material consumption (e.g. coal, natural gas, iron ore, etc.), and *CO₂C* are the costs associated to a possible carbon tax, discounted by the rate *r*. Since costs are not strictly defined, a standard deviation of the *LCOS* was calculated. Different agents might perceive costs differently based on local conditions. The standard deviation represents the heterogeneity of investors. Using the *LCOS* and its standard deviation, investor preferences were calculated between all technology pairs (Eq. 2).

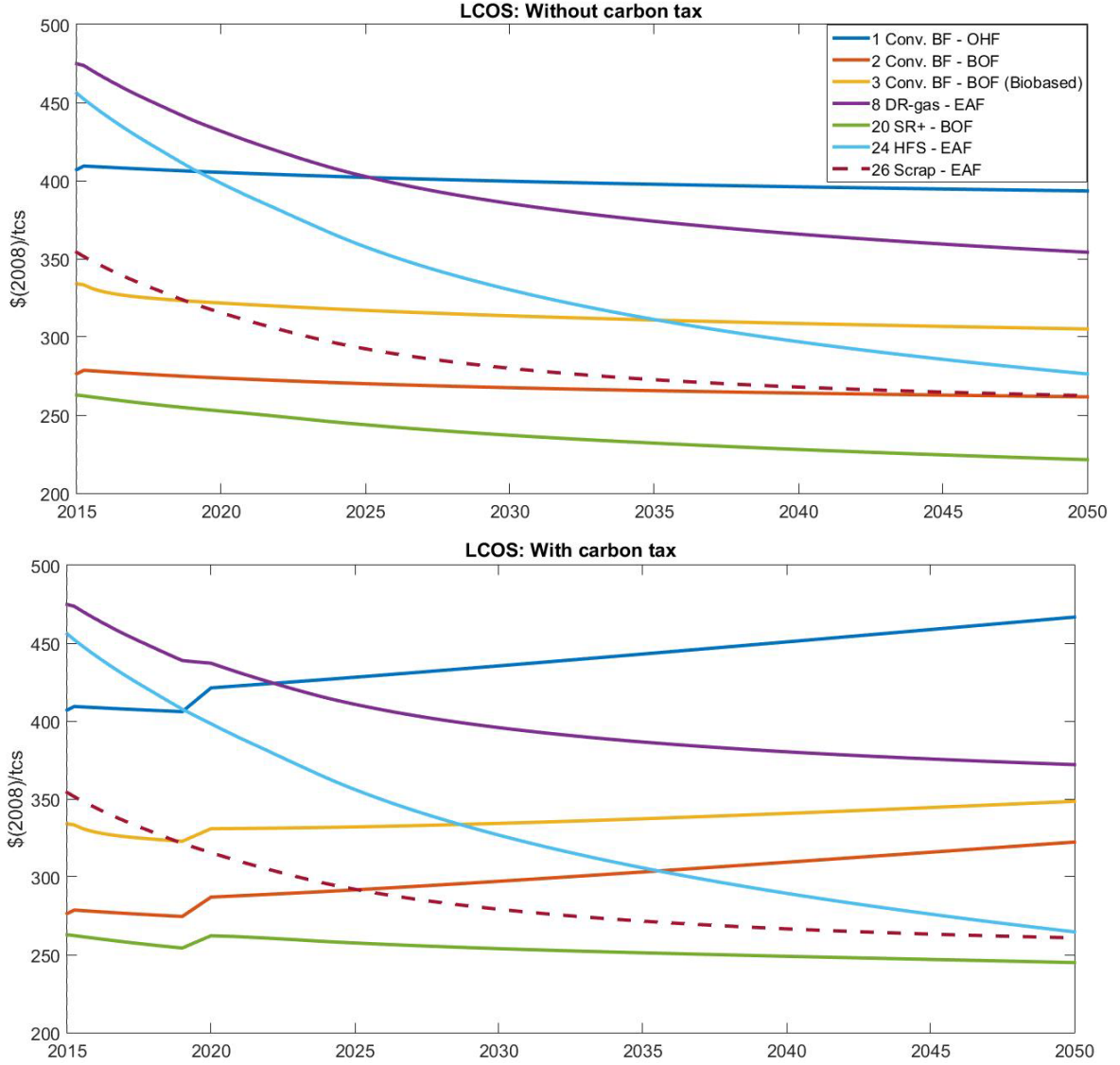
$$\text{Eq.2 } \sum_j \Delta S_{j \rightarrow i} = \Delta S_i = \sum_j S_i S_j \cdot (F_{ij} A_{ij} - F_{ji} A_{ji}) \cdot \Delta t$$

where *A* is the replacement rate from one technology to another. A uniform distribution was assumed for the commission time of all the plants. So for each year a share equal to $1/LT$ of the plants will be decommissioned. Only these plants are eligible for replacement. Matrix *A_{ij}* contains the replacement rates between technology *i* and *j*, according to the constraints of build-time of technology *i* and lifetime of technology *j*. Eq. 2 can be split up in three parts. First, the term *S_i · S_j* can be regarded as description of technological lock-in. This value can only be large when the market shares of both technologies are close to 0.5. Second, the *F_{ij}* and *F_{ji}* terms depict the investor choices. And third, the *A_{ij}* and *A_{ji}* terms depict the natural rate of replacement of one technology by another. This is dependent on the lifetime of the technology to be replaced and the buildtime of the technology replacing it.

Besides end-of-lifetime replacements, investor might also choose to scrap their technology *j* and replace it by another technology *i*, if the production of an additional unit of crude steel by technology *j* appears to be more expensive than the lifetime costs of an alternative technology *i*. The calculation of before of end-of-lifetime replacements was calculated by eq. 3.

$$\text{Eq.3 } \sum_j \Delta SE_{j \rightarrow i} = \Delta SE_i = \sum_j S_i S_j \cdot (FE_{ij} SR_i - FE_{ji} SR_j) \cdot \Delta t$$

Figure 3 Conceptual illustration of the effect of learning-by-doing on the *LCOS*, with (top panel) and without (bottom panel) a carbon tax (applied from 2020 onwards, increasing linearly from 10 \$₂₀₀₈ to 50 \$₂₀₀₈), for several chosen technologies.



Note: Average material/energy costs were assumed for this conceptual illustration.

where, SR is the scrapping rate, which is depends on the inverse payback period minus the share of integrated steelworks that naturally reach end-of-lifetime. FE is the investor preference, similar to that of eq.2, with the exception that now the marginal costs of one technology and the lifetime costs of another technology are now compared, instead of the LCOS.

To mimic incremental innovation within a technology group, a learning rate was applied to both the investment costs and material consumption. Over time the investment costs associated to building a new plant of the same type will decrease due to learning-by-doing. Also less energy will be required to produce 1 tcs (ton of crude steel). The effect of the learning rate on the LCOS (with and without a carbon tax implemented) is illustrated in figure 2.

Many studies have stated that the inclusion of scrap in the steelmaking process is important to reduce the emission intensity of the iron and steel industry. Scrap can become available by recycling end-of-life cars, appliances, and by decommissioning of buildings [2]. Lifetimes of steel in each product group plays an important role as this dictates when certain portions of the steel stock become available as scrap [56]. Regional specific data on historical steel use, lifetimes, and loss rates were

extracted from Pauliuk et al. [56]. Furthermore, we followed the assumptions made by Morfeldt et al. [2] of increasing lifetimes and decreasing loss rates over time because of anticipated increase of societal focus on recycling. As a result of scrap availability, the need for virgin materials can vary, which changes the costs of steel production and amount CO₂ emitted.

3.3. Scenario setting

The diffusion of technologies and the development of CO₂ emissions were evaluated as a result of several policy portfolio scenarios. We assumed three cases of carbon taxes: low rate, medium rate, and high rate (see table 3). In this study, the effects of several carbon taxes applied in the East Asian countries were investigated, see table 3.

Table 3 Policy portfolio settings.

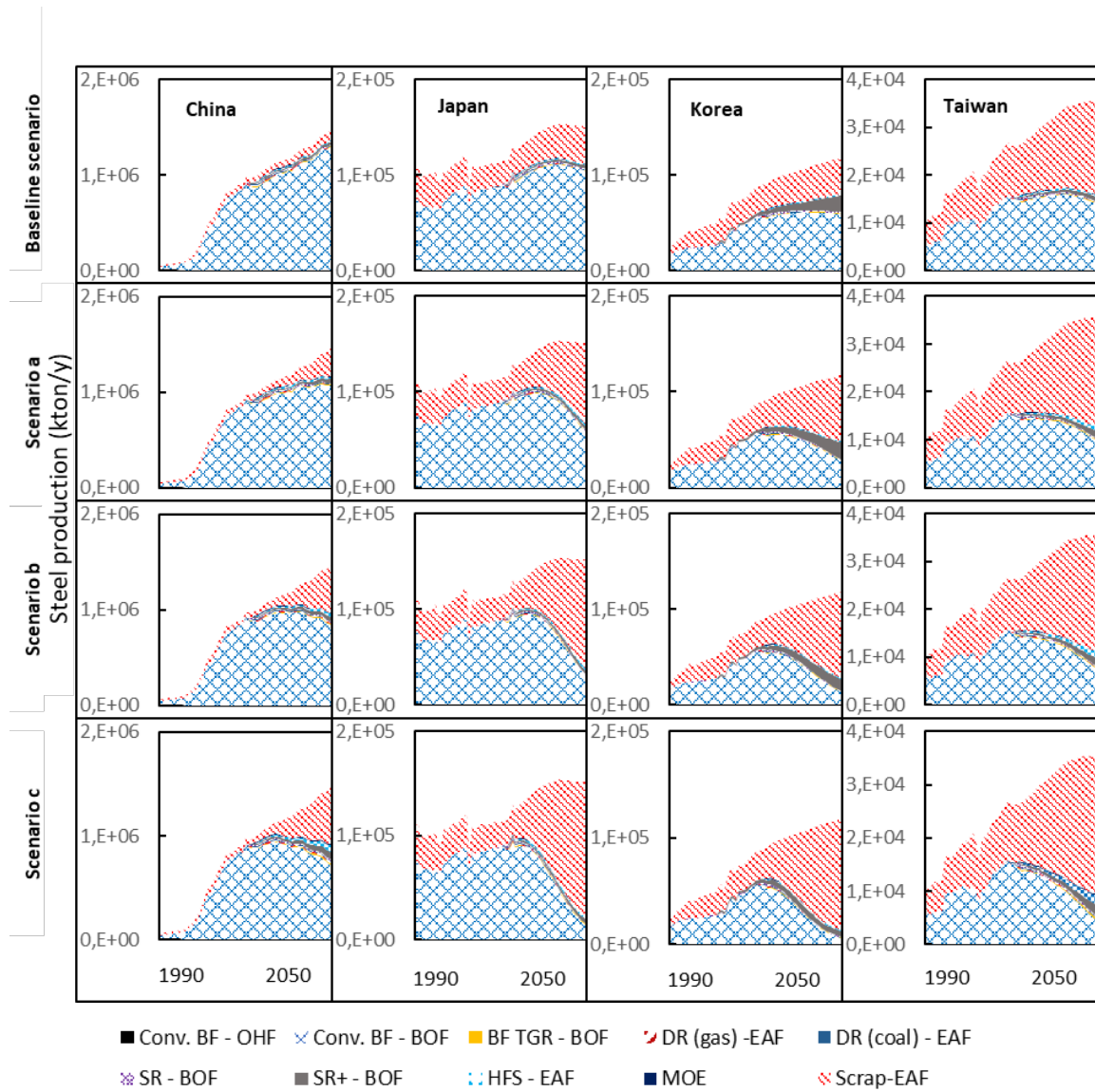
Baseline scenario	No policies	-
Scenario a	Low carbon tax case	10\$ ₂₀₀₈ to 50\$ ₂₀₀₈ (2020-2050)
Scenario b	Medium carbon tax case	10\$ ₂₀₀₈ to 100\$ ₂₀₀₈ (2020-2050)
Scenario c	High carbon tax case	10\$ ₂₀₀₈ to 200\$ ₂₀₀₈ (2020-2050)

4. Results

4.1 Technological diffusion

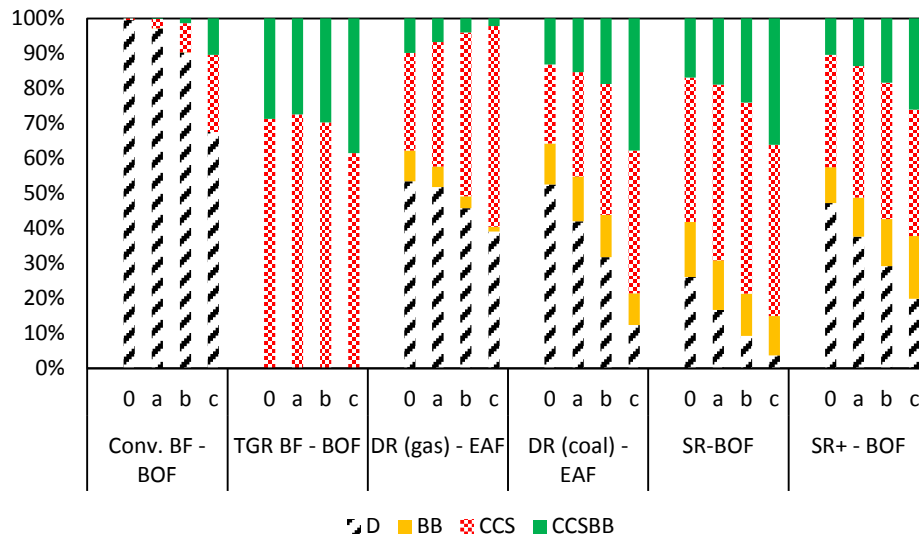
Under baseline conditions, no major changes of the technology mix was expected. Yet, only Korea shows diffusion of the SR+ - BOF route (see figure 3). As the severity of the low carbon policies increases, the SR+ -BOF route becomes more expensive and will reduce in market share in favour of the Scrap-EAF route. FTT:Steel simulated under all scenarios little diffusion of novel technologies, with the exceptions of China and Taiwan that show some diffusion of the HFS-EAF route under the most stringent low carbon policy scenario (c). Most of the market competition occurs between the Conv. BF-BOF and Scrap-EAF routes, because these two technologies have the largest shares. These two are locked-in and constrain the market penetration of novel technologies. Also, lifetimes of the plants are long (25 – 35 years) and therefore not that many replacements take place. Under the effect of carbon taxes, the simulation showed that investors prefer the Scrap-EAF route at the expense of the Conv. BF-BOF route.

Figure 4 Technological diffusion for the countries of interest (per column) and for each scenario (per row). Total steel production projections were taken from the macro-econometric model E3ME [4].



Although the diffusion of novel technologies is low, the circumstances in China are such that investors increasingly choose for biobased, CCS, or CCS + biobased options under the more stringent low carbon policy scenarios. See figure 5. Note that of the technology groups depicted, only Conv. BF – BOF and SR+ - BOF gain substantial market shares (45-88% and 2-6.5% respectively). Under the circumstances of high carbon taxes, combined with high substitution rates between variations within a technology group, the low carbon variations can gain an advantage over the default option of each technology group. Without a carbon tax, the low carbon variations will not gain significant market shares within each group. Biobased options are simply too expensive in general due to high costs of biomass. Only in combination with CCS, consumption of biomass becomes competitive under the stringent low carbon policies due to negative emissions.

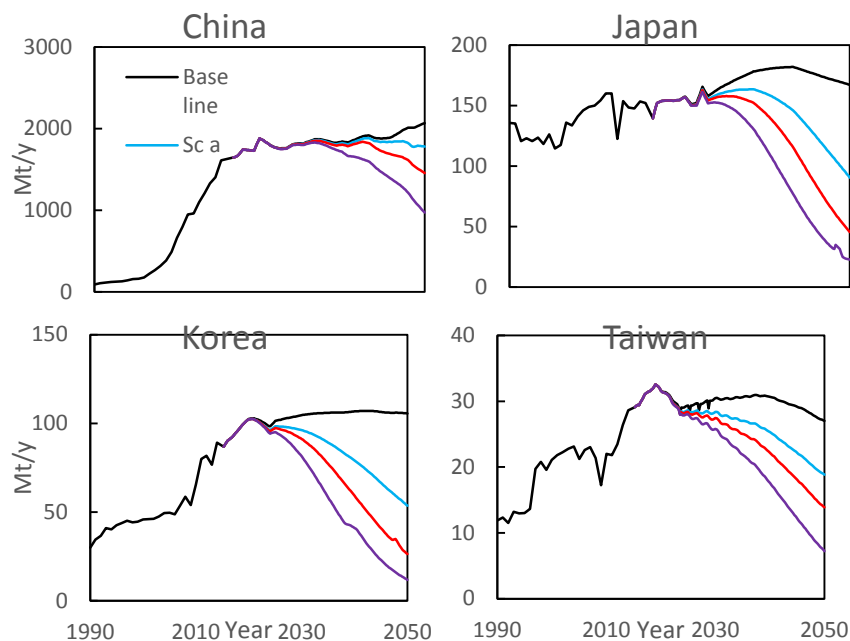
Figure 5 Shares of D (default), BB (Biobased), CCS (Carbon capture and storage), and a combination thereof (CCSBB) within each technology group in 2050 for each scenario (0, a, b, and c).



4.2. Environmental impact

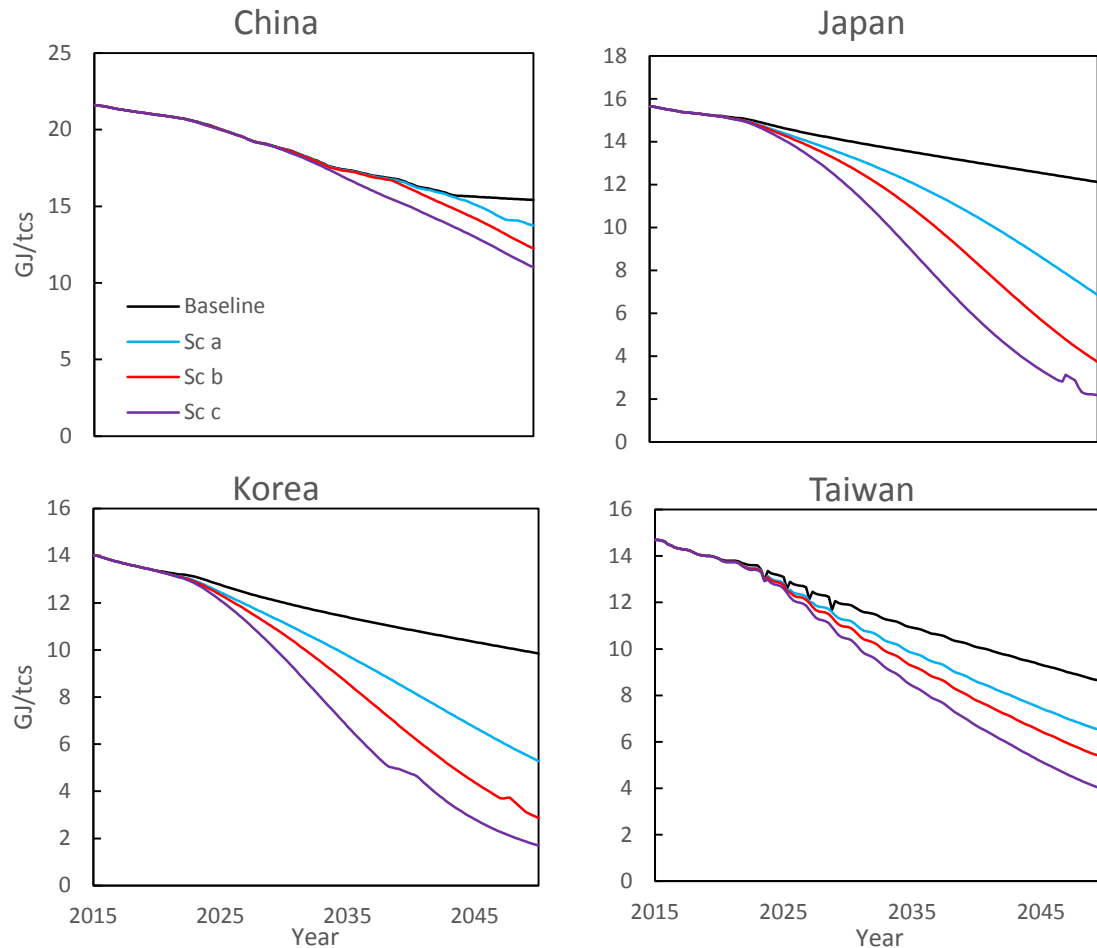
As expected, under all scenarios the emissions drop compared to baseline. The most invasive policy portfolio (scenario c) have a great effect on the emissions in Japan and Korea. Emissions were reduced by 86% for both countries under scenario c (compared to 2014). For China the reduction was 40%. The Taiwanese iron and steel industry reduced emissions by 75%. See figure 6. The most prominent reason of emission reduction can be found in the large increase in the market share of the Scrap-EAF route.

Figure 6 Development of CO₂ emissions of the entire iron and steel industry per country of interest.



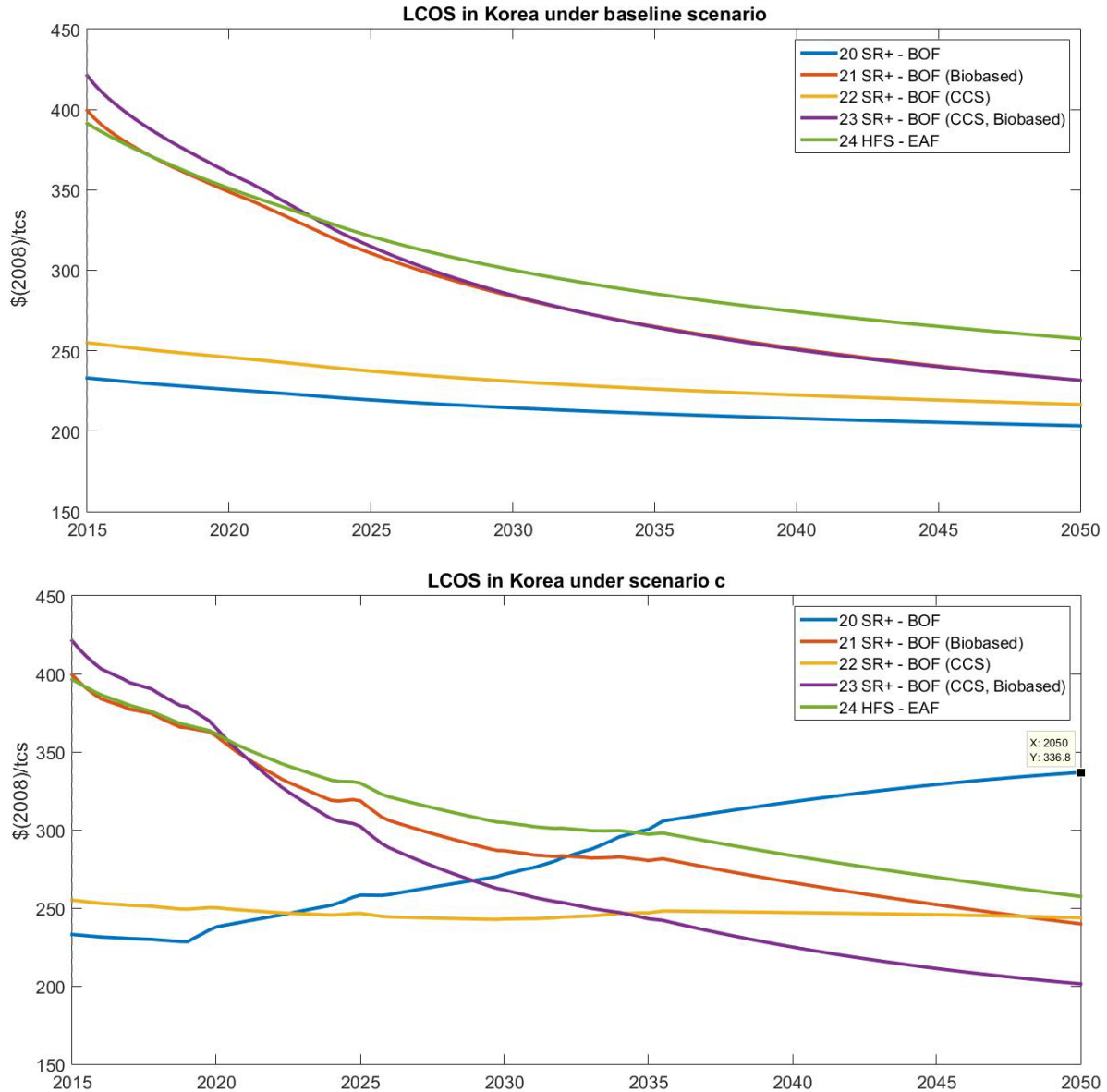
Like the emissions, under all carbon tax scenarios the average energy intensity decreases. This is mainly attributable to the increase of Scrap-EAF, and partly to an increase of energy efficiency and a decrease in investment costs due to learning-by-doing.

Figure 7 Development of energy intensity over time of the entire iron and steel industry for each of the country of interest.



The LCOS of novel technologies changes over time due to learning-by-doing. In FTT:Steel this means a decrease in CAPEX and a decrease in the amount of material consumption, i.e. an increase in energy efficiency. Figure 8 shows the development of the LCOS of all variations of the SR+ - BOF technology group and the HFS-EAF route under the baseline scenario and scenario c. The SR+ - BOF has low emissions, but still increases a lot in costs under scenario c. For SR+ - BOF (CCS), it remains the same. The CCS unit does not remove all CO₂ so it is still affected by the carbon tax. When CCS is combined with biomass consumption there will be effectively negative emissions, so this technology type becomes much cheaper more rapidly.

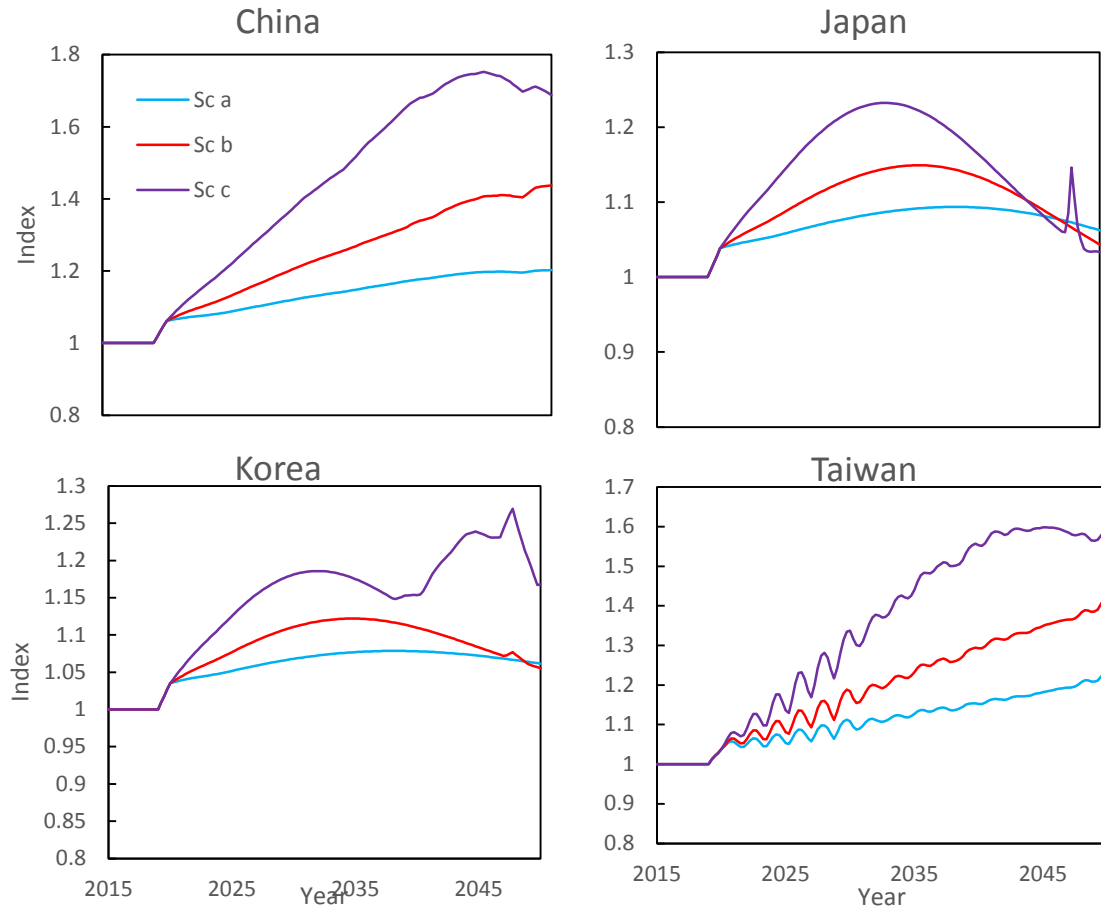
Figure 8 Comparison of LCOS for several novel technologies between scenario c and f.



4.3. Price development

As a result of the carbon tax, the conventional, fossil intensive processes of steelmaking become more expensive. This will increase the price of one ton of crude steel, which was calculated as the weighted average of the LCOS by market share. Figure 9 illustrates the development of the steel prices over time compared the development of the steel prices under the baseline scenario. The wiggly lines in Taiwan are caused by variability of the available scrap. The peaks in Korea and Japan can be explained by the reduced availability of scrap due to the large increase of Scrap-EAF. When the supply of scrap cannot meet the demand, the Scrap-EAF route has to purchase an intermediate iron product (from other plants) which leads to additional emissions and costs under the low carbon policy scenarios.

Figure 9 The development of the average crude steel price for each country of interest and for each low carbon policy scenario. The prices are relative to the development of the average steel price under baseline conditions.



5. Discussion & Conclusion

Most of the historical production data was gathered from the World Steel Association [9]. However, the production data was not on the same disaggregated level as the it is in FTT:Steel. Assumptions were necessary which may affect diffusion pathways. A detailed model such as FTT:Steel is susceptible to the quality of the input data and the assumptions made. Due to lack of data on investment costs, it was assumed that the figures are applicable globally. Besides regional explicit values for investment costs, also the amount of materials consumed on a regional basis is uncertain.

As section 4.1. shows, Scrap-EAF replaced the Conv. BF-BOF route in the policy scenarios (mainly c). In reality, Scrap-EAF will not be able to replace Conv. BF-BOF easily, as the steel they produce are usually of different quality and are therefore used by different sectors. This argument applies to most alternative steelmaking processes. Currently, only the Conv. BF – BOF route is able to produce steel of varying qualities for varying end-users, this explains it large market shares globally. In this study, we assumed that other processes will able to produce steel of varying qualities through incremental innovation to meet the steel demand of more market segments over time. Another reason why diffusion of Scrap-EAF might be constrained, is the quality of the scrap available. EOL steel is usually contaminated with other metals or coatings. In most cases, such steel scrap can be used to produce steel construction beams, but the automotive industry requires higher quality of steel.

In this study we successfully set up an innovation model that describes technological diffusion of the iron and steel sector under the influence of various policy portfolios. FTT:Steel was based on commercially available technologies and those currently in the research phase. Modelling innovation is not without obstacles. Technological breakthroughs are difficult, if not impossible, to predict and may happen at any moment. In reality a greater rate of diffusion of novel technologies could occur in the iron and steel sector, or new technologies that have not been considered in this study may arise in the future.

Regardless of the low rate of diffusion of novel technologies, all low carbon scenarios show large decreases in emissions. The iron and steel sector knows slow diffusion rates due to the longevity of the plants, which was corroborated by the results presented in this study. Technological competition mostly takes place between the two most dominant steelmaking routes, the Conv. BF-BOF and the Scrap-EAF routes. Within the Conv. BF – BOF route, investor preferences fall in favour of CCS and CCS in combination with biobased material consumption under the stringent low carbon policy scenarios. Under the conditions presented in this paper, these technologies leave little room for other technology groups. All scenarios show an increase of Scrap-EAF at the expense of Conv. BF – BOF in all countries except China. Scrap availability is a constraint for China and therefore the replacement rate is in part negated. In order for novel technologies to gain significant market shares, a market pull policy specific for novel technologies should be implemented.

In the near future, FTT:Steel will be coupled to the Energy-Environment-Economy Macroeconometric (E3ME) model. This coupling would yield feedbacks between innovation as modelled by FTT:Steel and energy prices by E3ME (through connection with FTT:Power [4]). The standalone FTT:Steel model presented here used constant prices for hydrogen and biomass consumption. Especially the price of hydrogen might decrease over time due to innovation of hydrogen production processes. The feedback of material/energy prices could affect innovation in the iron and steel industry. This illustrates the importance of coupling FTT:Steel to an economy-wide model, as the results of one may affect the results of the other through feedbacks.

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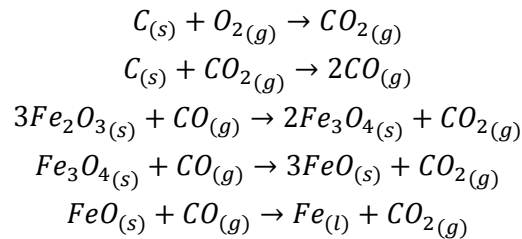
Appendix

FTT:Steel Model Description

1. Complete process

1.1. General principal

General chemical reaction. In nature iron oxide occurs mostly as hematite (Fe_2O_3) or magnetite (Fe_3O_4). Iron ore rich in hematite or magnetite can be utilised directly due to their high share of iron atoms. Some ore is mined as lump ore, which means these are larger masses of iron containing minerals. Lump ore can be used directly as a feed material and therefore the demand for lump ore is high and so is its price. Other iron ore is mined as ore fines, and these require agglomeration in a sinter or pellet plant before it can be fed into the ironmaking process. Historically, a carbon source such as coke or charcoal was used to reduce iron oxide [1]. While many different processes exist to reduce iron oxide to iron, the general principal and chemical reactions are similar [2]. See the reaction scheme below:



Reaction scheme 1: The reduction of iron oxides by a carbon source.

The carbon source is oxidised by oxygen in the air, which generates carbon dioxide. If the temperature is high enough, carbon dioxide can be reduced to carbon monoxide by the carbon source. A hot gas rich in carbon monoxide will rise within the shaft and will reduce the iron ore or the porous agglomerates [3]. Since iron ore contains a lot of impurities, these have to be extracted from the mixture. Therefore, a fluxing agent such as limestone is added to the furnace and this reacts with the impurities. For some processes, the metallic iron will be melted at the bottom of the furnace and on top of that a slag layer will form which contains the impurities. This can now be easily separated, while the liquid iron (also called hot metal) can be poured off to continue further processing [4]. For other processes that do not smelt the iron will have more difficulties of getting rid of the impurities.

The iron product can have varying names depending on the production technology, and whether it proceeds to further refinement immediately or not. Regardless, the iron now has a carbon content of approximately 4%. The steelmaking process further refines this to around 0.04%, depending on the desired steel quality, by exposing the liquid hot metal to oxygen. This oxidises the carbon and any remaining impurities [4].

1.2. Precursor Steps

Coke plant. When coal is extracted from the Earth's crust it contains a fair share of impurities. Using coal as-is for reducing iron ore, yields poor quality steel. The volatiles and impurities are driven off by heating the coal in an oxygen deprived environment [4]. The coking process results in a pure carbon source which has a higher energy density than the raw coal that was used as input [5]. Many different coking processes of varying performances exist [6], however, in this study we focussed on a general coking process and make no distinction between different technologies, since this is not a bottle-neck process.

Sinter plant. Not all iron ore comes in the suitable form to feed directly into the ironmaking process. Ore fines require agglomeration to become suitable for the reduction process. In a sinter plant ore fines are heated and upon heating they form larger, porous granules [2].

Pellet plant. Another way of agglomerating ore fines is by pelletising the fines. Ore fines are rolled into balls and subsequently baked. This results in porous pellets where a reducing gas can easily be passed through [2].

Not included in the model. Some integrated steelworks have an onsite lime kiln to produce burnt lime with limestone as input. This is used as fluxing agent in the iron ore reduction process to get rid of the impurities. However, the overall limestone/lime use is low, so this process does not bare the largest portion of the costs associated with steel production. A similar argument applies for an oxygen plant [7].

1.3. Ironmaking Technologies

1.3.1. Currently Commercially Exploited Technologies

Conventional Blast Furnace (Conv. BF). The most common method to reduce iron ore to iron is through the use of coal as reducing agent [8]. This is performed in Blast Furnaces (BF). A back draw is necessity of high quality input materials such as high grade coal and lump ore. Both are becoming increasingly rare and subsequently more expensive. Ways to circumvent this is to upgrade lower grade materials by converting coal into coke and by producing iron ore agglomerates from iron ore fines [2].

First, coke is loaded into the BF to provide heat and produce carbon monoxide gas. Then iron ore agglomerates, coke and fluxing agent are loaded from the top. These get heated as they slowly descent into the furnace [4]. In modern BFs air or oxygen and pulverised coal get injected to provide additional heat. Carbon reacts to oxygen to yield carbon dioxide and this can react to carbon again to produce the reducing agent carbon monoxide (see reaction scheme 1). The produced gases rich in reductant ascend within the shaft and reduce the iron ore. At the bottom, the additional heat melts the iron to a liquid and the impurities containing slag forms on top of it.

Gas Based Direct Reduced Iron (DRI-gas). Directly reducing iron ore was in the centre of attention during the 60's and 70's [9]. In a gas-based direct reduction plant natural gas is reformed to syngas, which is a mixture of carbon monoxide and hydrogen gas. The reducing gas is then passed through porous pellets and the iron oxides are oxidised. This happens below the melting point of the pellets. Processes such as Midrex, HYL III, IT3mk, FASTMELT, ULCORED, and Circored are example of gas-based DR processes.

Coal Based Direct Reduced Iron (DRI-coal). Coal-based direct reduction is very similar to gas-based direct reduction, with the exception that in this case coal is used to generate a gaseous reducing agent. Low quality coal can be used instead of coking coal for this technology group. Some of the coal-based DR technologies are Circofer, Coal-based HYL, SL/RN, Coal-based Rotary Kiln.

Smelt Reduction (SRI). A relatively new iron ore reduction technology is the Smelt Reduction route. Within in this production route technologies such as COREX, FINEX, HIs melt, DIOS, Cyclone Converter Furnace, Romelt, and Tecored are encompassed. These technologies have little to no need for precursor processes (coke making, pelletizing, and sintering), if the iron ore is of sufficient quality. However, ore quality is usually an issue, so it was assumed that SRI production requires a supply of pellets [10].

Since for most of the aforementioned technologies data is lacking and only few are commercially in use, the decision was made to agglomerate these technologies and base it primarily on the most abundantly utilised technology which is the COREX process [11,12].

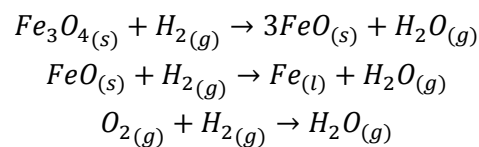
1.3.2. Future Novel Technologies

Blast Furnace Top-gas Recycling (BF TGR). In 2004, a group of European steel companies and research institutions established ULCOS, which stands for Ultra-Low Carbon Dioxide Steelmaking. Its goal is to establish technologies which can reduce CO₂ emissions per ton of steel by 50% in 2050 [13]. One of the technologies projected to decrease emissions in the iron and steel sector is Blast Furnace – Top Gas Recycling (BF TGR). This principle is the same as a conventional BF, however, with the inclusion of Carbon Capture and Storage (CCS) and efficient recycling of top gas a reduction in emissions and energy use can be established [14]. A pilot plant was set up in Sweden for some time, but has been discontinued [15]. While it is possible to use the TGR technology without CCS, most sources seem to indicate that CCS will be an integral part of TGR BF (e.g. [13–15])

Advanced Smelt Reduction (SR+). The Advanced Smelt Reduction pathway was mainly based on the HIsarna and FINEX technologies. HIsarna is one of the ULCOS technologies and it is the most promising and advanced technology in the development route so far [13,16]. It is a smelt reduction ironmaking process and skips an entire production step; it doesn't require coke, sinter and pellets making. It reduces CO₂ emissions by at least 20% compared to the Blast Furnace route. When combined with CCS, HIsarna reduces CO₂ emissions by 80% [16].

The other technology included in this aggregate group is FINEX. The Korean steelmaking company POSCO holds the rights of exploitation for the FINEX process. Its characteristics are that, like HIsarna, it does not require pre-processing of iron ore or coal [17,18]. While SR+ is actually implemented to some degree (see the HIsarna pilot plant in the Netherlands, and the only FINEX plant in Korea, see also 2.2), it is treated as a novel ironmaking technology due to its lack of commercialisation.

Hydrogen Flash Smelting (HFS). Existing technologies primarily use carbon as the reducing agent, however, also hydrogen can theoretically be used as reducing agent [19]. Ideally, this could originate from a source of biomass [13]. In FTT:Steel we are not concerned with the hydrogen source, since this is calculated by the E3ME model. However, it would require substantial amounts of hydrogen and electricity [20]. The reactions taking place during this process are different from the other processes, see below (reaction scheme 2):



Reaction scheme 2: The reduction of iron by a hydrogen source.

The formation of water vapour is exothermic, much like a hydrogen-based fuel cell, and provides the heat to facilitate the reduction of iron oxides[21].

1.3.3. Agglomeration of ironmaking technologies

Name of Technology Group	Conventional Blast Furnace	Blast Furnace incl. a Top Gas Recovery Unit	Gas-based Direct reduction	Coal-based Direct reduction	Conventional Smelt Reduction	Advanced Smelt Reduction	Hydrogen Flash Smelting
Abbr.	Conv. BF	TGR BF	DRI (gas)	DRI (coal)	SRI	SRI+	HFS

Technologies included	-Conv. BF -BF incl. PCI	-TGR BF	-Midrex -HYL III -FASTMELT -ITmk3 -ULCORED -Circored	-Coal-based HYL -SL/RN -Circofer -Coal-based Rotary Kiln	-COREX -Hismelt -Dios Process -Cyclone Converter Furnace -Tecnored	-FINEX -Hisarna	-HFS
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1.4. Steelmaking Technologies

1.4.1. Currently Commercially Exploited Technologies

Open Hearth Furnace (OHF). The oldest technology currently still in use, but decreasing in market share, is the Open Hearth Furnace (OHF) [8]. The OHF was the most-used steelmaking technology in the world for most of the 20th century. It is becoming more and more obsolete and nowadays only accounts for around 1% of the total steel production [8]. Iron containing materials are loaded step-by-step into the furnace and heated until melted. The OHF steelmaking is a batch process and its production rate is therefore slow [2].

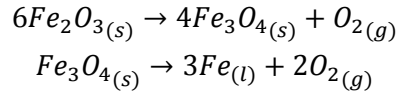
Basic Oxygen Furnace (BOF). The Basic Oxygen Furnace (BOF) has overtaken the OHF technology and is currently the dominant steel production route. BOF plants are integrated with Blast Furnaces (BF). The integrated path of BF-BOF is highly energy intensive due to the production of coke and sinter [14]. The input materials for the BOF are about 80% liquid hot metal from the BF and the remainder is steel scrap. Oxygen (at least 99.5% pure) is blown into the BOF at high velocities, this leads to decarburization and purification of the hot metal. The silicon and carbon contained in the hot metal is oxidized which then releases great amounts of heat which in turn melts the scrap or pig iron [4]. For that reason, a coolant needs to be added to the molten mixture. Up to 30% of scrap or DRI and about 15% of iron ore can be added in terms of weight ratio for this purpose [2]. This shows that the feed materials for the BOF can vary a lot.

Electric Arc Furnace (EAF). Whereas most integrated steelmills consist of the BF-BOF route, the minimills consists almost exclusively of Electric Arc Furnaces (EAF) [4]. This is the only steelmaking technology that is used for 100% secondary steelmaking (i.e. only using steel scrap as input). In that case it has a significantly lower energy intensity compared to BF-BOF, because no precursor steps are required. However, it is limited by steel scrap availability [14,22]. In regions of the world where natural gas and/or coal is relatively cheap, EAF steelmaking is integrated with Direct Reduced Iron (DRI) technologies. The energy intensity of gas-based DRI production can be lower than the energy intensity of the Blast Furnace route. However, that depends on factors like size, and fuel and ore characteristics. Gas-based DRI-EAF does not need coke making, but uses pellets for the ironmaking [4]. The coal-based variant has a higher energy intensity [23].

1.4.2. Future Novel Technologies

Molten Oxide Electrolysis (MOE). All other steelmaking technologies need pre-processed iron ore or steel scrap to produce steel. The Molten Oxide Electrolysis (MOE) can produce steel directly from iron ore. A joint research programme of the American Iron and Steel Institute and the US Department of Energy are researching the possibility of an all-electric technology. The only way to accomplish this is to reduce the iron ore in a molten oxide bath. Molten Oxide Electrolysis (MOE) is currently still in the research phase [24,25]. Boston Electrometallurgical Corp. is pursuing this technology to make it commercially available. Also the European ULCOS focussed on all-electric steelmaking named ULCOWIN and ULCOLYSIS [13]. Electrolysis from aluminium ore is already applied in the

aluminium industry [26]. The principles are the same, with the difference of input materials. Iron ore is not easily electrolysed due to its chemical properties. Given the lack of data on this unexploited technology, it was decided to base its economic characteristics on that of the aluminium industry [26]. Also for the MOE technology group reduces iron oxides in slightly different way from a chemical perspective (reaction scheme 3) [27]:



Reaction scheme 3: The electrolysis of iron oxides.

The IEA has concluded that it seems unlikely that this technology group would gain a significant market share in the next 20 to 40 years due to the high amounts of electricity consumption and the associated losses [28].

1.5 General assumptions

In this research, we assumed that investors would choose to build self-reliant integrated steelworks. This means that the ironmaking capacity has to be able to fully meet the steelmaking capacity. In reality, steel scrap is co-melted and thereby reduces the need for raw materials, i.e. a reduction in the capacity utilisation rate of the ironmaking steps and hence the pre-cursor steps. In addition, not all integrated steelmills are not capable of being self-reliant, so these would have to import materials. However, in this model it is assumed that investors will invest in integrated steelworks where the capacity of the precursor steps and ironmaking step can fulfil the steelmaking step entirely. This is justified as the difference between importing precursor materials or producing them onsite are expected to be small. In fact, including the precursor steps could be regarded as a way of estimating the import costs of precursor materials. Further, we assume that: 1 ton of crude steel requires 1.1 ton of intermediate iron supply (e.g. pig iron or direct reduced iron); approximately 1.7 ton of iron ore (agglomerates) is required for 1 ton of primary iron production (PIP); and it takes 1.33 ton of raw coal to produce 1 ton of coke.

Also, since there are only a limited number of engineering companies capable of constructing integrated steelmills, it was assumed that investment costs would not vary much among regions, so globally applicable values were assumed. Operation and maintenance costs are, unlike investment costs, not assumed to be fixed. If an integrated steelmill consumes relatively a lot of scrap, then the precursor steps are not needed for steel production and therefore not used to their full capacity so the operation and maintenance costs change as a result of that.

1.6 Biomass

While biomass could be processed within the integrated steelworks [29], we assumed that it purchased (solid biomass or biogas). This is justified, since the production costs would be incorporated within the purchase value. In this study we assumed that all direct uses of coal and natural gas can be replaced directly by charcoal and biogas [30]. However, when it comes to coke production, charcoal is unsuitable to fully replace coal. Only to some degree charcoal can replace coal, but the majority of the feed material has to be coal [29,31]. FTT:Steel assumes a replacement rate of 10% [29].

The consumption of biomass for the bio-based production routes was estimated as a result of the energy densities. For all non-biobased processes consuming coal, it is assumed to be coking coal (~33 MJ/kg). The exception for this is coal used for the coal-based DRI production technologies. These use lower grade coal (~25 MJ/kg). Charcoal is assumed to have an energy density of ~30 MJ/kg.

- Coking coal – Charcoal replacement ratio = $33/30 = 1.1$
- Lower grade coal – Charcoal replacement ratio = $25/30 = 0.83$

- For biogas, an identical energy density was assumed as natural gas.

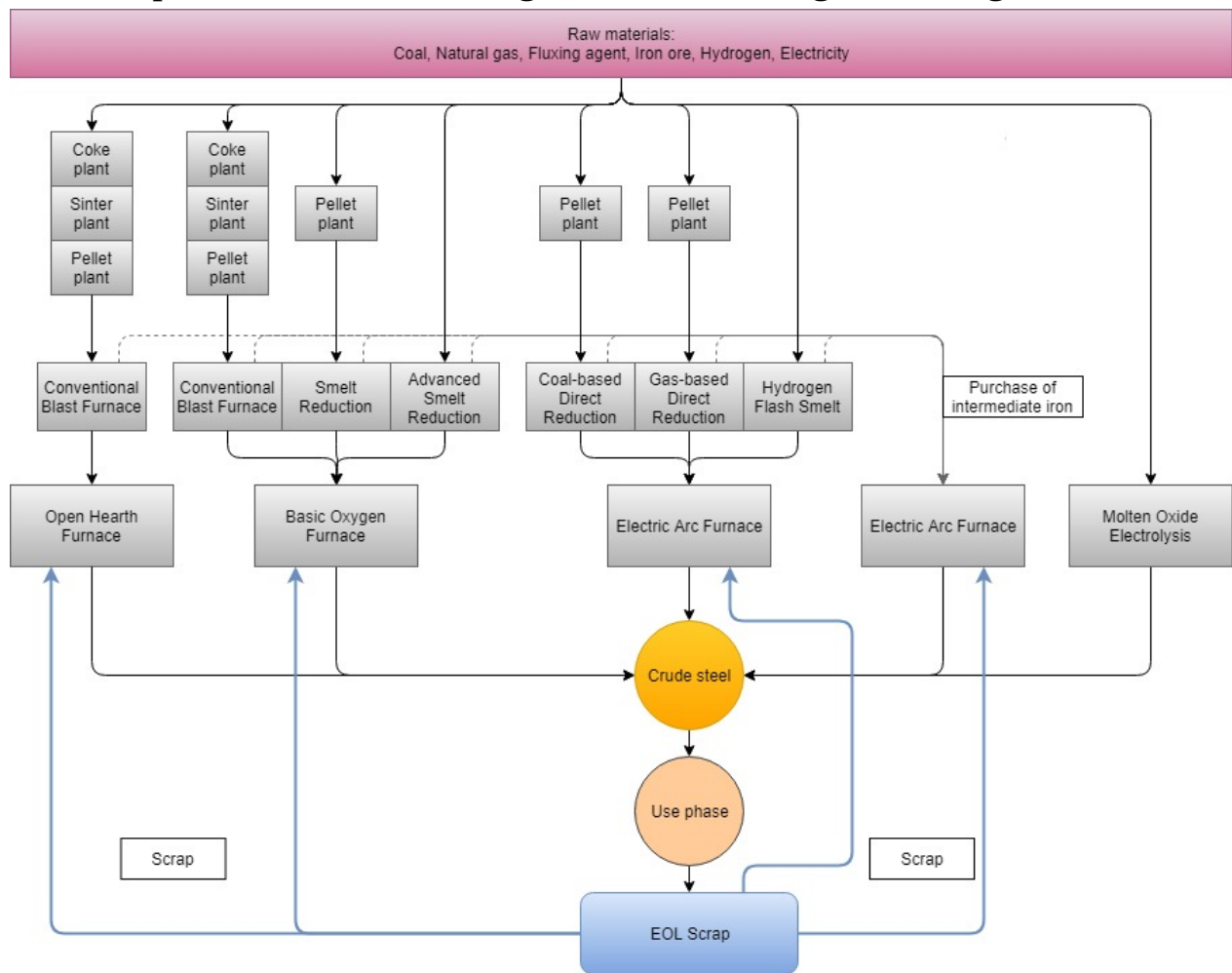
1.7 Carbon Capture and Storage

The carbon dioxide avoidance costs of the Zero Emission Platform's (ZEP) report were used [32]. While the avoidance costs were reported specifically for the power sector, the numbers published in this report were adapted to become applicable to CCS in the iron and steel industry. We assumed an increase of capital investment costs of 50 \$₂₀₀₈/tCO_{2, avoided} [32] and an addition of 5 \$₂₀₀₈/tCO_{2, stored} [33] to the operation and maintenance costs.

For biomass combined with CCS technologies, the CO₂ emissions of the biomass was calculated as a result of the corresponding emission factors. While these emissions are not taken into account regarding carbon tax costs (see 4.5), they are taken into account to calculate the CO₂ avoidance costs (i.e. increase in capital investment costs and operation and maintenance). In the case of biogas consumption, the same emission factor as natural gas consumption is taken (appr. 55 kg CO₂-eq./GJ). For charcoal, the emission factor of 2.53 tCO₂/t. This is based on an average carbon content of 70% and the assumption that all carbon is oxidised to CO₂.

Multiple more technology groups could be added to FTT:Steel, such as Circored and Circofer (DR technology group) which do not require pellets [34] unlike most other DR technologies (e.g. Midrex [35]). Even so, data is in such cases often scattered and sources are not always in agreement. When including more technologies individually, instead of aggregating them with others into a technology group, we might increase the model accuracy, but also expose the model to greater parameter uncertainty. In the end, a model such as FTT needs to find a balance between model accuracy and parameter uncertainty.

1.8 Complete overview of integrated steelmaking technologies



Ironmaking	Steelmaking	Integrated Steelmaking	# Variations
Conv. BF	OHF	Conv. BF – OHF	1
Conv. BF	BOF	Conv. BF – BOF	4
TGR BF	BOF	TGR BF – BOF	2
DRI (Gas)	EAF	DRI(gas) – EAF	4
DRI (Coal)	EAF	DRI(coal) – EAF	4
SRI	BOF	SRI – BOF	4
SRI+	BOF	SRI+ – BOF	4
HFS	EAF	HFS – EAF	1
-	MOE	MOE	1
-	EAF (scrap-based)	Scrap-EAF	1
Total number of technologies included in FTT:Steel			26

2. Data Collection

2.1. Historical data

While this study focusses on the East Asian steel industry, it is imperative to use a global model to evaluate the impact of policies on technological diffusion and emissions as a result thereof. Technological learning can take place in other parts of the world and this would affect technologies in East Asia. Connection to the macro econometric E3ME model yields impacts to other parts of the economy, but this is not discussed here.

Historical production of crude steel (total, and by Open Hearth Furnace, Basic Oxygen Furnace, and Electric Arc Furnace), pig iron, and direct reduced iron were extracted from numerous Worldsteel Statistical Yearbooks, e.g. [8]. Total steel production was gathered from 1900 to 2014. From 1970 to 2014, production data was extracted from the World Steel Association [8] and for the period before we assumed a growth rate of 3.5% annually. Here, we followed the recommendation by Grosse [37] to estimate the steel production from 1900 to 1970. Technological specific steel production data was gathered from 1990 to 2014, also mainly using data from the World Steel Association [8]. However, from this data the historical production of steel through the Conv. BF-OHF, Conv. BF-BOF, DR (gas+coal)-EAF, and Scrap-EAF could be estimated. Yet, the resolution of the World Steel Association data was of insufficient resolution. For example, pig iron is not only produced in BFs but also in SR processes. This data was not explicitly published. Historical data on SR utilisation was lacking all together. A few sources describe the use and production capacity of the COREX and FINEX process (SR and SR+ production technologies resp.) [10]. And while the World Steel Association does report DR production, it does not distinguish between gas-based and coal-based DR. By cross referencing this data to other sources, the historical production data for both technology groups could be estimated [36].

2.2. Special cases

- Small blast furnaces in **Brazil** use biomass (charcoal) to reduce iron ore and/or iron agglomerates to iron [38].
- **India** is one of the few countries in the world to utilise coal-based direct reduction. The amount of coal-based DRI production was based on data from Laplace Conseil [36].
- While **India** has a fair share of induction furnaces, these were modelled to be EAF instead.
- **India** at least has one COREX plant [11].
- Coal and iron ore quality are low in **China** and therefore the material consumption was altered.
- **China** utilises the COREX technology, which is designated as a SRI-BOF steel production route [10,11].
- The utilisation rate of **Chinese** steel production was approximately 50% in 2015 [39].
- The **Korean** steel company POSCO possesses over the commercial rights of the FINEX technology. This is an advanced smelt reduction technology part of the SRI+ - BOF route. A steelmaking capacity of 1.5 Mt/y was reported [17].
- The COREX technology was utilised in **Korea** [10,11].
- Also in **South Africa** the COREX technology is utilised, but capacity levels were not reported [11].
- Under the ULCOS programme, a novel ironmaking technology plant was launched in **the Netherlands**. The construction of the HIsarna plant with a capacity of 60 Mt/y was finished in 2012 [16].

3. Full mathematical framework of FTT:Steel

3.1. LCOS

The investment costs affect the LCOS only during the building phase, while all other aspects affect the LCOS only during its use phase.

$$LCOS = \frac{\sum_0^{\tau} \frac{IC/CF + OM + FC + CO_2C}{(1+r)^t}}{\sum_0^{\tau} \frac{1}{(1+r)^t}}$$

where IC is the investment cost, and it is divided by the capacity factor (CF) and the lead time, OM are the operation and maintenance costs, FC are the costs of material consumption (e.g. coal, natural gas, iron ore, etc.), and CO_2C are the costs associated to a possible carbon tax, discounted by the rate r . The standard deviation of the $LCOS$, representing the heterogeneity of agents, is then calculated according to equation 2.

The $LCOS$ function is also adjusted by a gamma value which seeks to correct the model's $LCOS$ calculation as a result of a lack of data. The gamma value is calculated by looking at the last 4 historical years and the first 4 modelled years. The average incline per technology in terms of market share changes are compared and the gamma value is chosen such that the average incline is the same before and after the start modelling [42]. Investor preferences are calculated based on the $LCOS$ including the gamma value.

$$sdLCOS = \frac{\sum_0^{\tau} \sqrt{\left(\frac{sdIC}{CF}\right)^2 + sdOM^2 + sdFC^2}}{(1+r)^t}}{\sum_0^{\tau} \frac{1}{(1+r)^t}}$$

For the calculation of the $LCOS$ and $sdLCOS$, a discount rate of 5% was assumed to be applicable to the iron and steel sector, since the rate of return of investment is not high for the iron and steel sector.

3.2. Investor preference

The differences between the $LCOS$ values for all technologies are used to calculate probabilistic investor preferences for each technology. To describe the preference of investors for choosing technology i or technology j and vice versa, equation 3 is used.

$$Eq.3 \ F_{ij} = \frac{1}{2} + \frac{1}{2} * \frac{2}{\sqrt{\pi}} \int e^{-\left(\frac{LCOS_j - LCOS_i}{sdF_{ij}}\right)^2} , F_{ji} = 1 - F_{ij}$$

where sdF_{ij} is the standard deviation due the standard deviations of the $LCOS$ of technology i and j respectively. See equation 4.

$$Eq.4 \ sdF_{ij} = \sqrt{2 \cdot (sdLCOS_i^2 + sdLCOS_j^2)}$$

Investor preference are affected by regulations (see 4.2.).

3.3. Market share changes

The change in market share is proportional to market share of technology i divided by its build-time, market share of technology j divided by its lifetime, the preference matrix F , and time-step Δt . Only when a plant technology j reaches end-of-life, investors could choose for technology i , where i is constrained by its build-time. See equations 5 and 6.

$$\text{Eq.5 } \Delta S_{j \rightarrow i} \propto \frac{S_i}{BT_i} \cdot \frac{S_j}{LT_j} \cdot F_{ij} \cdot \Delta t$$

$$\text{Eq.6 } \Delta S_{i \rightarrow j} \propto \frac{S_j}{BT_j} \cdot \frac{S_i}{LT_i} \cdot F_{ji} \cdot \Delta t$$

By summing over all different technologies j , the total market share change for technology i is produced. See equation 7.

$$\text{Eq.7 } \sum_j \Delta S_{j \rightarrow i} = \Delta S_i = \sum_j S_i S_j \cdot (F_{ij} A_{ij} - F_{ji} A_{ji}) \cdot \Delta t$$

where A is the replacement rate from one technology to another. A uniform distribution was assumed for the commission time of all the plants. So for each year a share equal to $1/LT$ of the plants will be decommissioned. Only these plants are eligible for replacement. Matrix A_{ij} contains the replacement rates between technology i and j , according to the constraints of build-time of technology i and lifetime of technology j .

$$\text{Eq.8 } A_{ij} = \frac{\kappa}{BT_i \cdot LT_j}$$

where κ is a time constant divided by the build-time of technology i and the lifetime of technology j , and vice versa for A_{ji} . Note that matrix A is not symmetrical. For cases where the replacement occurs faster, the A matrix can be adapted. Such cases are fuel switching and CCS retrofitting.

The market share changes are only affected by investor choices, government imposed regulations, and government imposed technology additions (see 4.1).

3.4. Learning rate and technological spill over

Due to a global increase in steel production capacity for a technology, all past experiences are applied to the newly built steelworks. This means these are less capital intensive and run more efficiently than their predecessors.

Due to all market share changes, the production capacities for each technology change as learning occurs. This means that future capital investment costs, emission factors, and material consumption efficiency will be reduced with cumulative technological investment, given in equation 9, 10 and 11 respectively.

$$\text{Eq.9 } IC_{i,t} = IC_{i,t-1} \cdot (1 - LR_i) \cdot \frac{GCAP_{i,t} + PIC_{i,t}}{GCAP_{i,t-1}}$$

$$\text{Eq.10 } ME_{i,j,t} = ME_{i,j,t-1} \cdot (1 - LR_i) \cdot \frac{GCAP_{i,t} + PIC_{i,t}}{GCAP_{i,t-1}}$$

Where $GCAP$ is the production capacity of technology i , and b is the learning rate. $GCAP$ includes technological spill over. PIC is the perceived increase in capacity due to R&D and/or energy efficiency investments, which promote technological learning. Similar technologies will also benefit from learning of another technology.

As stated in the introduction, most of the prior research focussed on incremental innovation and thereby improving the energy efficiency and reducing the emission intensity. This is exactly what the learning rate tries to capture.

3.5. Scrap Availability

Many studies have stated that the inclusion of scrap in the steelmaking process is important to reduce the emission intensity of the iron and steel industry. Scrap can become available by recycling end-of-life cars, appliances, and by decommissioning of buildings [16]. Lifetimes of steel in each product group plays an important role as this dictates when certain portions of the steel stock become available as scrap [17]. Regional specific data on historical steel use, lifetimes, and loss rates were extracted from Pauliuk et al. [17]. Furthermore, we followed the assumptions made by Morfeldt et al. [16] of increasing lifetimes and decreasing loss rates over time because of expected increase of durability and an increasing societal focus on recycling.

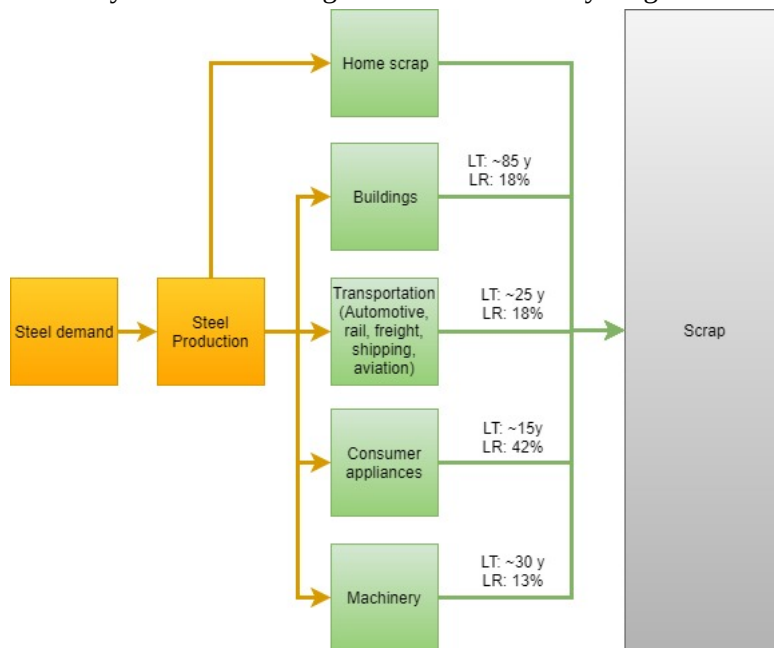


Figure 10

The Scrap-EAF route mostly uses scrap, but since steel demand outweighs scrap availability, the growth of this technology is limited. Other primary steel producing technologies also utilise steel scrap to some degree. In countries where scrap availability is not a problem, about 150 kg of scrap are co-melted for the production of 1 tcs [18].

Regions	Sectoral Split				Est. Lifetimes				Loss rates				Recycling Rates			
	Transport	Machinery	Construction	Products	Transport	Machinery	Construction	Products	Transport	Machinery	Construction	Products	Transport	Machinery	Construction	Products
1 – Belgium	0,3	0,1	0,47	0,13	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
2 – Denmark	0,32	0,11	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
3 – Germany	0,3	0,1	0,47	0,13	13	20	50	10	0	0	0,1	0	0,82	0,87	0,82	0,58
4 – Greece	0,32	0,11	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
5 – Spain	0,32	0,11	0,47	0,1	20	30	75	15	0	0	0,1	0	0,82	0,87	0,82	0,58
6 – France	0,3	0,1	0,47	0,13	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
7 – Ireland	0,32	0,11	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
8 – Italy	0,32	0,11	0,47	0,1	20	30	50	15	0	0	0,1	0	0,82	0,87	0,82	0,58
9 – Luxembourg	0,3	0,1	0,47	0,13	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
10 – Netherlands	0,3	0,1	0,47	0,13	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
11 – Austria	0,32	0,11	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
12 – Portugal	0,32	0,11	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
13 – Finland	0,3	0,1	0,47	0,13	20	30	75	15	0	0	0,1	0	0,82	0,87	0,82	0,58
14 – Sweden	0,22	0,2	0,43	0,15	20	30	50	15	0	0	0,1	0	0,82	0,87	0,82	0,58
15 – UK	0,22	0,2	0,43	0,15	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
16 – Czech Republic	0,3	0,1	0,47	0,13	13	20	50	10	0	0	0,1	0	0,82	0,87	0,82	0,58
17 – Estonia	0,3	0,1	0,47	0,13	20	30	50	15	0	0	0,1	0	0,82	0,87	0,82	0,58
18 – Cyprus	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
19 – Latvia	0,3	0,1	0,47	0,13	20	30	50	15	0	0	0,1	0	0,82	0,87	0,82	0,58
20 – Lithuania	0,3	0,1	0,47	0,13	20	30	50	15	0	0	0,1	0	0,82	0,87	0,82	0,58
21 – Hungary	0,32	0,11	0,47	0,1	13	20	50	10	0	0	0,1	0	0,82	0,87	0,82	0,58
22 – Malta	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
23 – Poland	0,29	0,25	0,31	0,15	13	20	50	10	0	0	0,1	0	0,82	0,87	0,82	0,58
24 – Slovenia	0,3	0,1	0,47	0,13	20	30	100	15	0	0	0,1	0	0,82	0,87	0,82	0,58
25 – Slovakia	0,25	0,29	0,31	0,15	20	30	75	15	0	0	0,1	0	0,82	0,87	0,82	0,58
26 – Bulgaria	0,25	0,29	0,31	0,15	10	15	38	8	0	0	0,1	0	0,82	0,87	0,82	0,58
27 – Romania	0,22	0,2	0,43	0,15	10	15	38	8	0	0	0,1	0	0,82	0,87	0,82	0,58
28 – Norway	0,22	0,2	0,43	0,15	13	20	50	10	0	0	0,1	0	0,82	0,87	0,82	0,58
29 – Switzerland	0,32	0,11	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
30 – Iceland	0,3	0,1	0,47	0,13	20	30	50	15	0	0	0,1	0	0,82	0,87	0,82	0,58
31 – Croatia	0,3	0,1	0,47	0,13	20	30	100	15	0	0	0,1	0	0,82	0,87	0,82	0,58
32 – Turkey	0,25	0,29	0,31	0,15	10	15	38	8	0	0	0,1	0	0,82	0,87	0,82	0,58
33 – Macedonia	0,3	0,1	0,47	0,13	20	30	100	15	0	0	0,1	0	0,82	0,87	0,82	0,58
34 – USA	0,3	0,1	0,47	0,13	20	30	75	15	0	0	0,1	0	0,82	0,87	0,82	0,58
35 – Japan	0,3	0,1	0,47	0,13	10	15	38	8	0	0	0,1	0	0,82	0,87	0,82	0,58
36 – Canada	0,32	0,11	0,47	0,1	20	30	50	15	0	0	0,1	0	0,82	0,87	0,82	0,58
37 – Australia	0,22	0,2	0,43	0,15	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
38 – New Zealand	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
39 – Russian	0,3	0,1	0,47	0,13	20	30	50	15	0	0	0,1	0	0,82	0,87	0,82	0,58
40 – Rest of Annex I	0,3	0,1	0,47	0,13	20	30	50	15	0	0	0,1	0	0,82	0,87	0,82	0,58
41 – China	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
42 – India	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
43 – Mexico	0,22	0,2	0,43	0,15	20	30	50	15	0	0	0,1	0	0,82	0,87	0,82	0,58
44 – Brazil	0,11	0,32	0,47	0,1	13	20	50	10	0	0	0,1	0	0,82	0,87	0,82	0,58
45 – Argentina	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
46 – Colombia	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
Regions (continued)	Sectoral Split				Est. Lifetimes				Loss rates				Recycling Rates			

	Transport	Machinery	Construction	Products	Transport	Machinery	Construction	Products	Transport	Machinery	Construction	Products	Transport	Machinery	Construction	Products
47 - Rest of Latin	0,25	0,29	0,31	0,15	10	15	38	8	0	0	0,1	0	0,82	0,87	0,82	0,58
48 – Korea	0,29	0,25	0,31	0,15	10	15	38	8	0	0	0,1	0	0,82	0,87	0,82	0,58
49 – Taiwan	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
50 – Indonesia	0,22	0,2	0,43	0,15	20	30	100	15	0	0	0,1	0	0,82	0,87	0,82	0,58
51 - Rest of ASEAN	0,11	0,32	0,47	0,1	20	30	75	15	0	0	0,1	0	0,82	0,87	0,82	0,58
52 - OPEC excl	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
53 - Rest of World	0,25	0,29	0,31	0,15	20	30	75	15	0	0	0,1	0	0,82	0,87	0,82	0,58
54 – Ukraine	0,3	0,1	0,47	0,13	20	30	50	15	0	0	0,1	0	0,82	0,87	0,82	0,58
55 - Saudi Arabia	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
56 – Nigeria	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
57 - South Africa	0,22	0,2	0,43	0,15	10	15	38	8	0	0	0,1	0	0,82	0,87	0,82	0,58
58 - Rest of Africa	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58
59 - Africa OPEC	0,11	0,32	0,47	0,1	27	40	100	20	0	0	0,1	0	0,82	0,87	0,82	0,58

Material variability only depends on scrap availability. For each iteration the maximum scrap demand (*MSD*) is calculated based on the steel production figures of the primary steelmaking routes and the secondary steelmaking route.

$$\text{Eq. 11 } MSD_{k,t} = 0.3 \cdot \sum_i^{PST} SP_{i,k,t} + SP_{k,t,SST}$$

Where *SP* is the steel production in region *k* at time *t*. All *SP*'s are summed for all *i* that refer to primary steelmaking technologies (*PST*). This is multiplied by 30%, as 30% of the input may be scrap. The maximum scrap utilisation rate for the secondary steelmaking technologies (*SST*) route is 100%.

The scrap availability (*SA*) was calculated as result of historical steel stocks obtained from Pauliuk et al. [17].

$$\text{Eq.12} = \sum_p^{Productgroups} \eta_p \cdot \rho_p \cdot (1 - \gamma_p) \cdot \sum_i^{Technologies} SP_{k,i,t-EOL_p}$$

Where η is the share of steel in product group *p*, ρ is the recycling rate, γ is the loss rate of steel within product group *p*. *SP* the steel production at some time *t-EOL*.

Machinery, building, transportation, and household products were the four product groups considered for the calculation of scrap availability. For the historical steel stocks we followed Pauliuk et al.'s [17] assumption that the division among product groups remained unchanged. For future steel stocks, the shares were based on E3ME calculations (see 3.3 for a description). Following the methods of Morfeldt [16], the loss rate was set to gradually decrease while the recycling rate was set to increase. Unlike Morfeldt et al., the lifetimes of the product groups was also set to increase gradually.

If the *SA* is greater than the *MSD*, then the maximum scrap will be used as feedstock for the steelmaking technologies. The remainder will flow over to the next time iteration. However, if the *SA* is smaller than the *MSD*, then the available scrap will have to be divided over the technologies.

$$\text{Eq. 13 } SA_{k,t} \geq MSD_{k,t}: \begin{cases} SI_{i=SST,k,t} = 1 \\ SI_{i=PST,k,t} = 0.3 \end{cases}$$

$$\text{Eq. 14 } SA_{k,t} < MSD_{k,t}: \quad SI_{i=SST,k,t} = \frac{SA_{k,t}}{MSD_{k,t}} \cdot 1$$

$$SI_{i=PST,k,t} = \frac{SA_{k,t}}{MSD_{k,t}} \cdot 0.3$$

SI is the scrap input for technology i , in region k , at time t . These values are then entered into the inventory matrix (see table). The amount of primary iron production (PIP) equals $(1-SI) \cdot 1.1$ in case of the PST . In case of the SST and a lack of scrap availability, pig iron or DRI has to be purchased. This is denoted as primary iron input (PII), which is also equal to $(1-SI) \cdot 1.1$. Note that the costs of purchased PII is much higher than that of scrap. After all the parameters have been calculated, an input-output calculation of the Leontief type [19] is made to calculate the total consumption of raw materials and intermediate products (see eq.).

3.6. Variable resource consumption

Since scrap can be used as a feed material for most technologies scrap availability can affect the amount of virgin materials consumed.

The type of fuel can be highly variable, e.g. oil or natural gas can be used in a blast furnace to provide heat. Oil is usually added in minute amounts as a heating source and lubricant. In most cases, however, mainly coal is used as a heating source, so FTT:Steel does not consider oil as a heating source.

Table 4 Inventory matrix as used in eq. 11. For each iteration over time and production route, the correct ironmaking and steelmaking technologies and their material consumption get selected. As a result of the scrap availability calculation, the ratio scrap and primary iron production is calculated and entered as input for the steelmaking technology.

	Steelmaking technology	Ironmaking technology	Intermediate plants (coke plant, sinter plant, pellet plant)			Raw materials							
	Steel	Iron	Coke	Sinter	Pellets	Scrap	Coal	Natural Gas	Electricity	Iron ore	Limestone	Hydrogen	Biomass
Steel	...	...	...	...	...	...	...	...	...	...	...	...	...
Iron	...	...	...	...	...	...	...	...	...	...	...	...	...
Coke	...	...	...	...	...	...	...	...	...	...	...	...	...
Sinter	...	...	...	...	...	...	...	...	...	...	...	...	...
Pellets	...	...	...	...	...	...	...	...	...	...	...	...	...
Scrap	...	...	...	...	...	...	...	...	...	...	...	...	...
Coal	...	...	...	...	...	...	...	...	...	...	...	...	...
Natural	...	...	...	...	...	...	...	...	...	...	...	...	...

Gas													
Electricity	...	...	...	...	...	...	...	...	...	...	...	...	...
Iron ore	...	...	...	...	...	...	...	...	...	...	...	...	...
Limestone	...	...	...	...	...	...	...	...	...	...	...	...	...
Hydrogen	...	...	...	...	...	...	...	...	...	...	...	...	...
Biomass	...	...	...	...	...	...	...	...	...	...	...	...	...

$$\text{Eq. 15 } Inv_k = \left(\begin{pmatrix} 1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 1 \end{pmatrix} - \begin{pmatrix} X_{11} & \dots & X_{1n} \\ \vdots & \ddots & \vdots \\ X_{n1} & \dots & X_{nn} \end{pmatrix}_k \right)^{-1} * \begin{pmatrix} 1 \\ \vdots \\ 0 \end{pmatrix}$$

3.7. To be implemented in the future

Not only steel a ubiquitously traded commodity, also iron is traded. The main reason is quality assurance, Using one feedstock of iron source may lead to a decrease in quality. Therefore, a similar leveled cost calculation can be made to determine the minimum price of iron.

The price of scrap remains constant over time while it fluctuates in reality for a number of reasons. When the scrap is contaminated with copper or zinc then it is not very suitable as a feed material, since these metals are difficult to remove from the steel scrap. Then there is the variability in scrap availability. In times of shortages, the secondary steel producers will have to spend more on the material costs, due to a rise in scrap prices. The primary production routes may choose to co-melt more scrap if the costs of primary iron production (PIP) are too high [45], and likewise, secondary production routes may decide to purchase more iron when scrap prices are too high, or supply is too low, or as a quality assurance measure. A preference matrix could be built were the choice is made between iron or scrap based on the difference between the leveled costs of iron and the price of scrap.

4. Policies

4.1. Exogenous capacity additions

Governments may decide to directly influence the technology mix of the steel industry by commissioning new steel plants. This policy can also be used to insert proposed steel projects. Exogenous capacity additions are entered as absolute values which get converted to share additions.

$$\text{Eq. 16 } \Delta Sk_{i,t} = \frac{EXKA_{i,t}}{PSK_t}$$

$$\text{Eq. 17 } \Delta S_{i,t} = \sum_j \Delta Sm_{i,j,t} \cdot \frac{PSK_t - \sum_i EXKA_{i,t}}{PSK_t} + \Delta Sk_{i,t}$$

Where EXKA is the exogenous capacity addition, PSK is the projected steel capacity, Sk is the exogenous capacity addition share, and Sm is the endogenous market share additions. Because of the

exogenous share additions, the endogenous market share changes ($\Delta S_{i,j,t}$) have to be renormalized by a factor $(PSK_t - \sum_i EXKA_{i,t}) / PSK_t$ to make sure that projected steel capacity trajectory is followed and that the sum of all share changes equals 0.

4.2. Regulations

Whereas governments may decide to launch a certain iron- and steelmaking route into its technology mix, they may also decide that other technologies should be phased out for a number of reasons.

$$\text{Eq. 185 } IsREG_{i,t} = \frac{1}{2} + \frac{1}{2} * \frac{2}{\sqrt{\pi}} \int e^{-\left(\frac{S_{i,t} - REG_{i,t}}{S_{i,t}}\right)^2}$$

Where S is the market share of a technology, and REG is the market share that should not be exceeded by that technology. The regulations are then connected to the preference matrix where they will influence the market share changes calculation.

$$\text{Eq. 19 } F_{i,j} = F_{i,j} \cdot (1 - IsREG_i) \cdot (1 - IsREG_j) + IsREG_j \cdot (1 - IsREG_i) + \frac{1}{2} \cdot IsREG_i \cdot IsREG_j$$

$$\text{Eq. 20 } F_{j,i} = F_{j,i} \cdot (1 - IsREG_j) \cdot (1 - IsREG_i) + IsREG_i \cdot (1 - IsREG_j) + \frac{1}{2} \cdot IsREG_j \cdot IsREG_i$$

4.3. Taxes or subsidies on capital investment

The iron and steel industry is a highly capital intensive industry. To promote the diffusion of a certain technology, a policy can be implemented to reduce the capital needs. Or to make a technology unattractive, a tax can be applied to increase the capital needs for a certain technology. The subsidy or tax is subtracted or added to the 1st building year of the plant.

4.4. R&D and EE investments

Learning-by-doing is an important factor in innovation economics. A learning rate is defined as percentage in the decrease of the capital investment cost, emissions, or material consumption as a result of doubling of production capacity or investment.

In FTT:Steel it is possible to enter an value of investment done by governments for R&D research of certain technologies. The model will treat this as an additional perceived increase of capacity (PIC) by dividing the value of the investment by the capital investment costs of a technology

$$\text{Eq. 21 } PIC_RDI_{i,t} = \frac{RDI_{i,t}}{IC_{i,t-1}} = \frac{\$_{2008}}{\$_{2008} / tcs_{Capacity}} = tcs_{Capacity}$$

In a similar way, the PIC of energy efficiency is calculated. This only is added to

$$\text{Eq. 22 } PIC_EEI_{i,t} = \frac{EEI_{i,t}}{IC_{i,t-1}} = \frac{\$_{2008}}{\$_{2008} / tcs_{Capacity}} = tcs_{Capacity}$$

PIC then gets implemented in the learning rate calculation, in order to calculate the new capital investment costs and material efficiency. The latter translates to a reduction in technological specific emission factors and energy intensity factors.

$$\text{Eq. 23 } IC_{i,t} = IC_{i,t-1} \cdot (1 - LR_i) \cdot \frac{GCAP_{i,t} - GCAP_{i,t-1} + PIC_{i,t}}{GCAP_{i,t-1}}$$

$$\text{Eq. 24 } ME_{i,j,t}^* = ME_{i,j,t-1} \cdot (1 - LR_i) \cdot \frac{GCAP_{i,t} - GCAP_{i,t-1} + PIC_{i,t}}{GCAP_{i,t-1}}$$

if j = fuel

This way, it only makes sense to implement R&D investments for novel technologies and not for established technologies, since the value of PIC would contribute relatively little to the learning curve when $(GCAP_{i,t} - GCAP_{i,t-1})/GCAP_{i,t-1}$ is much larger than $PIC_{i,t}/GCAP_{i,t-1}$.

4.5. Carbon Tax

Emission intensive sectors can be incentivised to decarbonise by implementing a carbon tax. This can also be seen as an approximation of an emission trading scheme (ETS). A price per ton of carbon dioxide emission is set on a regional basis.

$$\text{Eq. 25 } CO_2C_{i,t} = CP_t * EF_{i,t}$$

Where CO_2C is the CO_2 costs in \$₂₀₀₈/tcs, CP is the carbon price in \$₂₀₀₈/tCO₂ and EF is the technology specific emission factor in tCO₂/tcs. COC gets fed in to the LCOS calculation, which works through to the market change calculation.

4.6. Fuel Tax or subsidy

An additional tax or subsidy may be applied to certain raw materials, in order to penalise or incentivise technologies to move away or promote technologies that heavily consume that certain raw material.

$$\text{Eq. 26 } FC_{i,t} = \sum_j MC_{i,j,t} \cdot MP_{j,t} \cdot (1 + MT_{j,t})$$

Where MC is the material consumption of material j per technology i at time t . MP is the material price, and MT is the additional tax or subsidy. FC gets then fed in to the LCOS calculation.

4.7. Direct subsidies

The Chinese authorities directly subsidised the iron and steel industry which has led them to develop into the global leader in steel production. Due to the subsidies, Chinese steelmakers were able to sell their steel cheaper compared to steelmakers in other parts of the worlds. Since it is unclear on how these policies are actually implemented, it is clear it affects the price at which Chinese steelmakers are able to sell their steel. Therefore, direct subsidies were implemented as a decrease in LCOS. However, it was assumed to be not technology specific, therefore all technologies receive the same direct subsidy. This means that technological diffusion is not affected since the difference of the LCOS between two technologies remains the same.

$$\text{Eq. 27 } LCOS_{i,t} = LCOS_{i,t}^* - DS_t$$

4.8. Capacity adjustments

The Chinese industry produces steel at low capacity utilisation rates due to an overcapacity of steel production facilities and stagnation in demand [39,48]. To remedy the overcapacity, the Chinese authorities have committed to reduce domestic capacity levels [39].

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