Projections for the Global Secondary Steel Market to 2050

Adam Mathews
Student Number: 3421503
Supervisor: dhr. prof. dr. E. Worrell
MSc Sustainable Development (track Energy and Resources), Utrecht University
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Abstract

This report investigates iron & steel demand and supply projections from 2011 to 2050. A Gompertz Function is used to relate GDP/Capita to in-use iron stocks, and this is then extrapolated using publicly available data to predict total global and regional in-use steel to 2050. In that year, total in-use iron stocks are predicted to be almost 70 billion metric tons against current estimates of 28 billion metric tons. Taking into account the turnover of three categories of stocks (vehicles, civil engineering and buildings), annual global demand by 2050 would be 2.2 billion, compared to today's 1.3 billion metric tons. In both of these cases, China is the largest single contributor. Iron ore stocks were then investigated to ascertain the sustainability of supply. Iron ore extraction was projected using two different scenarios, and taking into account Hubbert's *Peak Theory of Resource Extraction*, peak iron ore was forecast to occur between 2028 and 2041, after which supply will fall off exponentially, implying demand for secondary steel in 2050 to be between 1.1 and 1.25 billion tons. Finally, possibilities for scrap steel uprisings were investigated and found to be insufficient to provide for demand. Uprisings will grow to just over 1 billion metric tons in 2050, although this is an upper limit assuming zero losses.

Contents

1. Introduction

Iron is by far the most important metal element on the Earth, accounting for approximately 95% of all metal used in modern society, and up to 98% of this iron is used in steel-making (Yellishetty, Ranjith & Tharumarajah 2010). Iron and steel form the second largest raw material market in the world, behind only oil, and the industry is worth hundreds of billions of dollars a year (Wang, Müller & Graedel 2007). In 2010, global steel production rose to over 1.4 billion metric tons for the first time, a 67% increase since 2001. (WorldSteel 2011) The main driver for this growth was China, which saw a 313% increase in production from 2001, while the rest of the world experienced growth of just 9% overall (ibid.). During the same period, global trade in secondary steel (measured by quantity exported) increased by almost 90%, a comparable growth figure to that of iron ore, although absolute quantities of iron ore exported are a order of magnitude higher than for scrap (ibid.).

While iron and steel is easily the most important metal industry on the planet, it is also the single largest emitter of CO_2, contributing around 7-9% of global anthropogenic CO_2 emissions, or up to 25% of all industrial carbon emissions (Kim & Worrell 2002; Pauliuk, Wang & Müller 2012). In 1990 the industry was estimated to account for 12% of global energy consumption, a figure similar to that posited in 2007 by Wang, Müller & Graedel (they claimed 13%, but in a much larger world economy)

This rise in production appears to have been somewhat unexpected; as late as 2005 the World Energy Council, quoted in Hidalgo et al. (2005) was predicting world production of 1.3 billion tonnes in 2020, a figure surpassed ten years earlier than predicted. This sudden increase has revived questions about the sustainability of the industry, not just from an emissions and energy perspective, but also from possible supply issues.

Making up around 5% of the Earth's crust, and as much as 8.5% in certain rocks, iron is the fourth most abundant element on the planet (Müller et al. 2006; Yellishetty, Ranjith & Tharumarajah 2010). For this reason, it has long been assumed that there is more than enough of the resource to provide for indefinite economic development. However, as Yellishetty, Ranjith & Tharumarajah (2010) continue, a deposit should contain around 25% iron to be considered economically viable. This paper is one of the first to attempt to forecast iron ore production to 2050, and it finds potential issues around *peak iron* within the time span of this projection. Many papers (including Hatayama et al. 2010 and Pauliuk, Wang & Müller 2012) have recently begun to argue the importance of anticipating long-term trends in the iron and steel industry, both to create a 'sound material cycle' in the anthroposphere and because of long lifetimes and high capital expenditure associated with construction of facilities (factories and transport infrastructure, as well as recycling networks, not to mention the need for adequate regulation) for more sustainable iron and steel use.

1.1 Role of Steel Scrap

Since the end of World War II iron ore grades in the United States have decreased in iron content from around 50-60% to around 25-30% (Müller et al. 2006). This has led to a significant increase in the amount of water and energy use in the mining stage and was probably a major motivation in the US becoming the world leader in steel recycling. In 2008 the United States recycled 83.3% of all its end of life steel waste, meaning more steel is recycled in the US (by volume) than paper, plastic, glass, copper and aluminium combined (Recycling International 2009). While much of US steel production has been outsourced to Turkey and China, amongst others, over 60% of all steel produced in the US in 2010 came from Electric Arc Furnaces (see Section 2.2.2), which can use 100% recycled steel as a feed stock (WorldSteel 2011; Müller et al. 2006).

The advantages of recycling steel over primary production from iron ore are multitudinous. Not only is energy consumption reduced by at least 70% by recycling, CO_2 emissions are also cut by 58% (Wang, Müller & Graedel 2007; BIR.org 2012). Recycling one tonne of steel saves 642kWh of energy, 1.8 barrels of oil, 630 Kg of coal, 55 Kg limestone and 2.3 cubic metres of landfill. It also produces 76% fewer water pollutants, 85% fewer air pollutants and 97% less mining waste, as well as leaving at least 1.1 metric tonnes of iron ore in the ground for future extraction (BIR.org 2012). What is more, the steel recycling industry is about as old as steel itself and is a profit-making industry worth £5.6 billion in 2010 to the UK economy alone (BMRA 2012).

1.2 Motivation

As the son of an influential secondary metal broker, I grew up around scrap yards and was therefore exposed to the industry from a young age. Following in his footsteps I spent a number of years trading scrap metals internationally - primarily steel, but also aluminium and copper – in countries as diverse as the UK, Morocco, Russia, Hungary and India. It was during this time that I wrote a number of speeches, and hence performed some research in scrap steel, for my father to make in conferences from Brasil to China and the Ukraine.

While I enjoyed the more academic sides of the industry, I was less than amoured with the trading, and this was one of one of the major considerations in my decision to study for a masters' in Sustainable Development at Utrecht University. Approaching this issue from that perspective adds another layer to questions on the sustainability of exponential global economic growth. Although many studies have been performed into energy intensity and CO_2 emissions of the iron and steel industry - not least by my supervisor for this project prof. dr. Ernst Worrell (see for example Kim & Worrell 2002; Worrell et al. 1997), there is a shortage of projections which include considerations of scarcity of supply – of which this is possibly the first.

2. Current and Historical Supply and Demand

In order to make accurate predictions about future iron and steel use, a good knowledge of the past and current trends in production and supply is very important. The following section will look into trends in both iron & steel supply and demand, and will include a section on production methods which will inform the rest of the report.

2.1 Iron and Steel Supply

Global Steel production in 2010 was over 1.4 billion metric tons (otherwise known as tonnes or mt); nearly double the amount produced just 10 years earlier (in 2001 global production was around 850 million metric tons). China has been the major driver in this growth, ramping up production by around 400% in that time, to more than 600 million tonnes in 2010 (WorldSteel 2011). Although steel production was made an official Chinese national priority in the 1950s, it is only in the past few decades that stable production growth has become a reality, with new production capacity of several hundred million tonnes a year coming online throughout the last decade (Pauliuk, Wang & Müller 2012). This growth in capacity building has not been limited to China, however, and has left the world with an overcapacity in steel production facilities when compared to the amount of crude steel produced per year, a situation shown graphically in Figure 1. A number of other countries have witnessed notable crude steel production increases since 2000, with Indian production more than tripling, Turkish doubling, and crude steel output from Russia and Brazil also increasing. The other major steel producers; the EU, Japan and the United States, saw only slight changes (negative in the US and EU and positive in Japan) during the same ten-year period (WorldSteel 2011), partly as a consequence of the recession.

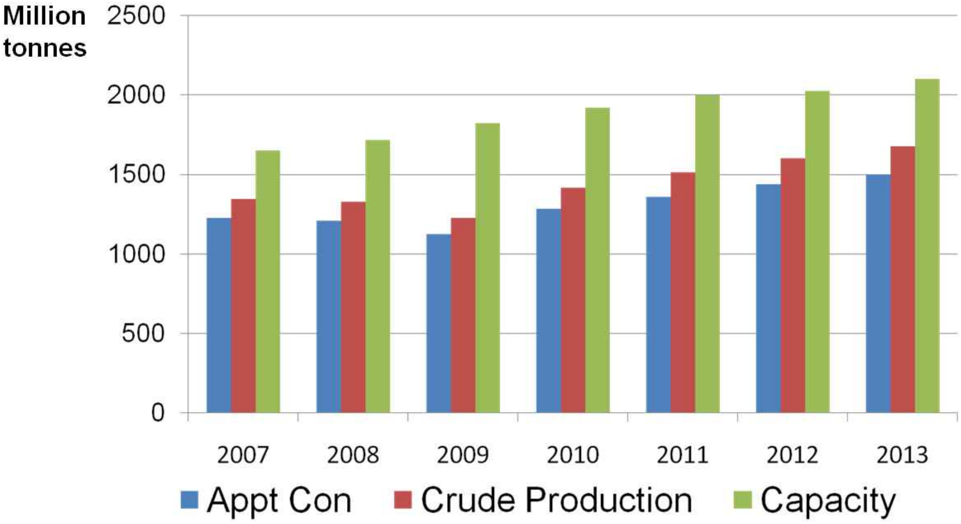

Figure 1: Graph comparing capacity with actual production of steel and its apparent consumption between 2007 and 2013 (from Manser 2011)

Iron ore remains the leading primary source for global steel production (Jorgenson 2011), with ore extraction exhibiting a similar increase to steel – from 930 million tonnes in 2001 to 1.96 billion tonnes in 2010 (WorldSteel 2011). As Yellishetty, Ranjith & Tharumarajah (2010) point out, in developed areas of the world, such as the EU, USA and Japan, iron ore production has fallen, sometimes dramatically. In 2009 the USA extracted just half the iron ore take out of the ground the previous year, while Europe's year-on-year drop was around 20% (WorldSteel 2011). Whether this is a trend or a recession-influenced one-off remains to be seen. Purchased scrap steel, in the meantime, makes up around a quarter of feed for new steel, although availability of scrap can be an issue in certain years (Wang, Müller & Graedel 2007; Jorgenson 2011). What is more, the scrap content of crude steel varies widely; Chinese steel is only around 13% recycled (Pickard 2011) while the USA recycles around 83% of scrap steel, although much of this is then exported, especially to Turkey (Danjczek & Price 2010).

2.2 Steel Production Methods

There are generally three stages required to produce useable steel. First, the iron ore is melted in a blast furnace to make pig iron, thus increasing the iron (also referred to as ferrous or Fe) content from around 60% to some 94% (Wang, Müller & Graedel 2007). At the beginning of the 20th century, pig iron output was larger than crude steel (78.5 million tonnes of pig iron against 72.4 million tonnes of crude steel), but by the end of the century steel production had dwarfed that of pig iron (around 800 million tonnes of steel against 500 million tonnes of pig iron) (Lyakishev & Nikolaev 2003). This can mostly be explained by a change in production techniques.

Having produced the feed stock, the second step involves converting pig iron to steel, with reduced carbon content and an iron content of over 98%, using a variety of methods (Lyakishev & Nikolaev 2003). For much of the last century, both iron refining and steel making took place in the same *integrated* metallurgical plant, often using open-hearth furnaces (OHF). However, by the early 1990s the technique had almost disappeared, to be replaced with either the Basic Oxygen Furnace (BOF) or the Electric Arc Furnace (EAF) (as shown in Figure 2) due to improved fuel efficiency, higher productivity, and lower capital costs (Yellishetty, Ranjith & Tharumarajah 2010; Lyakishev & Nikolaev 2003; Wang, Müller & Graedel 2007; Worrell et al. 1997). Indeed, BOF production can be a net energy *producer* in the form of gas or steam (Worrell et al. 1997). EAF, on the other hand, is not necessarily dependent on iron ore, as it can produce steel from 100% recycled input (Wang, Müller & Graedel 2007). In 2005, around 65% of world steel production came from BOFs, while 32% was from EAF and around 3% (mostly in Ukraine and Russia) from OHF (Yellishetty, Ranjith & Tharumarajah 2010). This has changed a little since then, mostly on the back of increased Chinese BOF production (see Figure 2). The different routes to steel production, along with expected energy intensities per tonne produced, are shown in Figure 3. The following two subsections describe the main two production methods, BOF and EAF, in a little more detail.

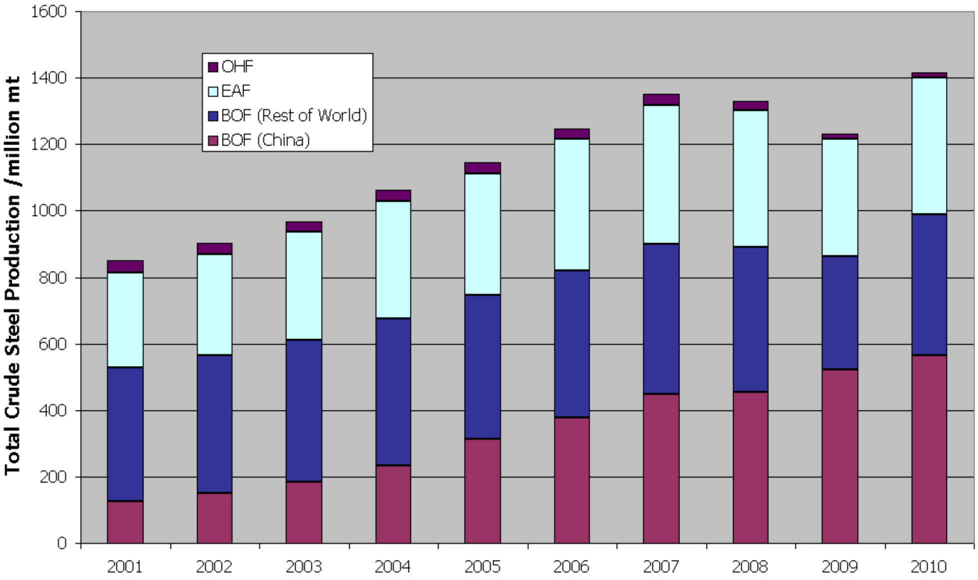

Figure 2: Amount of steel produced by production technique, from 2001 to 2010 (data from WorldSteel 2011)

The third step in the process involves transforming the crude steel into a saleable, finished commodity, either as a basic *flat* or *long* product, or as tubing, ingots, wire or railway track (for example). Although these processes use a lot of energy and will also produce ferrous yield losses, this report will only investigate up to the crude steel (end of second) stage, as displayed in Figure 3.

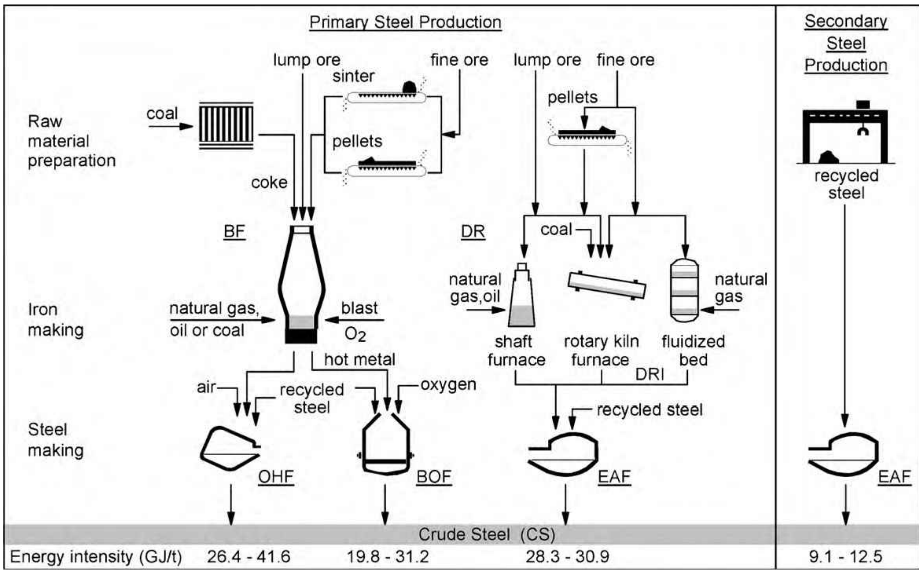

Figure 3: Steel production routes and energy intensities (from Yellishetty, Ranjith & Tharumarajah 2010)

2.2.1 Basic Oxygen Furnace (BOF)

Accounting for almost 70% of all the global crude steel produced in 2010, the BOF method remains by far the number one choice for crude steel production, not least due to the 450% increase in Chinese BOF production since the turn of the millennium (WorldSteel 2011). As can be seen in Figure 3, BOF requires iron ores to be processed into pig iron using a blast furnace (BF), before the oxygen furnace can be charged with the raw material. The molten iron is passed into the BOF, where industrial oxygen is used to reduce the amount of carbon in the steel by generating CO_2 in an exothermic reaction, which is then emitted (Yellishetty, Ranjith & Tharumarajah 2010). It should be noted that somewhere between 10-35% of the initial input to BOF furnaces is secondary steel, used to reduce the temperature of the molten iron (Yellishetty, Ranjith & Tharumarajah 2010; Steel Recycling Institute 2009).

2.2.2 Electric Arc Furnace (EAF)

Although steel produced in EAFs can also use iron ore as a feed source, as shown in Figure 3, the normal, and much more energy efficient use of EAFs involves charging the furnace with 100% steel scrap which is then melted using electrical energy imparted through carbon electrodes (Yellishetty, Ranjith & Tharumarajah 2010). As carbon content in the iron is not reduced in this method, CO_2 emissions are much lower than for other technologies, and are "mainly associated with consumption of the carbon electrodes" (ibid.). Although production using EAFs increased by 70% in the ten years from 2001, driven mostly by China (28 million metric tons extra installed capacity), India (21 million tonnes), Turkey (10Mmt) and Russia (10.5 million metric tons), the share of EAF to total production actually fell during that period, again largely due to China's huge increase in BOF production (Price & Danjczek 2011; WorldSteel 2011). This is shown clearly in Figure 2.

2.3 Demand for Steel

Two main statistics are used in this section, and throughout the rest of this report. They are *apparent consumption* and *stocks* (either anthropogenic/in-use or natural/virgin). Stocks are explained in some depth in the following subsection, while apparent consumption is calculated as the sum of production plus imports minus exports. Kelly & Matos (2011) define the relationship as follows

$$\text{Apparent Consumption} = \text{Production} + \text{Imports} - \text{Exports} \pm (\text{Stock Change})$$

Although, according to Steelonthenet.com (2012), the difference between apparent and real consumption is that the former does not include changes in stocks, the above equation *does* take that into account. Trade in finished steel, such as bars or plates, *is* included in apparent consumption, meaning that it could be defined as "the [total] amount of steel consumed in the domestic fabrication and manufacturing processes" plus imports (Hatayama et al. 2010).

Global apparent steel consumption doubled in the 25 years to 2010 (see Figure 4). Much of this growth can be attributed to China, where apparent steel consumption grew almost 9 times in that period, while consumption in the 'developed' countries of the EU, USA and Japan remained steady, with a slight decrease seen in 2010, probably due to the economic crisis. The low growth rates in the more developed countries (MDCs) is a reflection of changed consumption patterns as absolute demand for new houses, roads and vehicles has already been satisfied (Hatayama 2010). In the meantime those countries where infrastructure requires development, such as India, Turkey and Brazil, all saw increases of between 400-500 percent (worldsteel, 2011). These increases are expected to continue for the foreseeable future (UNEP 2011)

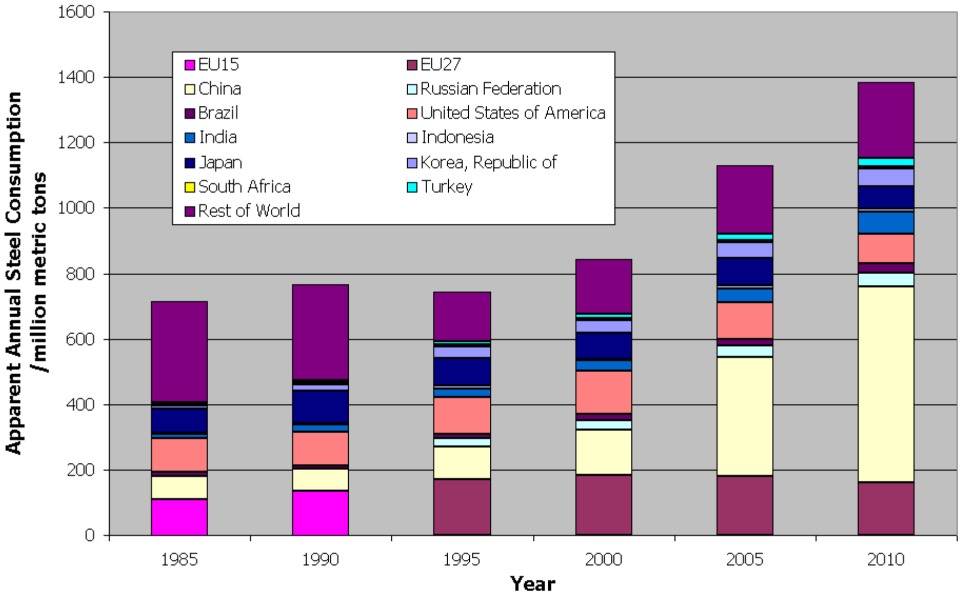

Figure 4: Apparent Annual Steel Consumption for the world, and a number of key economies. Data from Worldsteel 2011

2.3.1 Stocks

Stocks can be broken down into two kinds; natural (or virgin) stocks and anthropogenic (or in-use) stocks. Natural stocks are those deposited in the Earth through geological processes. Although there are many studies into natural stocks, quantifying them is no easy task. That said, organisations such as the USGS (US Geological Survey) make estimates which are publicly reported (UNEP 2011; Jorgenson 2011). The data shown in *Table 1* was produced by the USGS and estimates actual ferrous (Fe) reserves in iron ore to be 87 billion metric tons. The R/P ratio, representing the ratio of reserves against current annual production, gives a basic measurement of the lifetime of available resources at current production rates. However, it must be stated that on the same document, iron ore reserves are estimated to be in excess of 230 billion tonnes (giving a corresponding R/P ratio of around 100 years), while the figure used by Müller, Wang & Duval (2011) to produce Figure 5 was based on a lower estimate of 79 billion tonnes of natural stocks (indicated by iron content), while the in-use stocks shown in the figure are discussed below and in Section 3.1.2).

Anthropogenic, or in-use stocks are defined as the total amount of a certain material, iron and steel in this case, contained within a commodity used in human society with a potential for future recycling (Hatayama et al. 2010; Gerst & Graedel 2008). They can take a variety of forms, from the waste rock and impurities rejected at the production stage and found in tailings ponds, to metal held in stockpiles by governments or companies, and that found in in-use applications such as transport, construction, machinery and appliances, as well as some recoverable metals which may have been discarded (Müller et al 2006; UNEP 2011).

	Mine Production		Reserves		
	2009	2010	Crude Ore	Iron Content	R/P Ratio
USA	27	49	6900	2100	[redacted]
Australia	394	420	24000	15000	[redacted]
Brazil	300	370	29000	16000	[redacted]
Canada	32	35	6300	2300	[redacted]
China	880	900	23000	7200	[redacted]
India	245	260	7000	4500	[redacted]
Iran	33	33	2500	1400	[redacted]
Kazakhstan	22	22	8300	3300	[redacted]
Mauritania	10	11	1100	700	[redacted]
Mexico	12	12	700	400	[redacted]
Russia	92	100	25000	14000	[redacted]
South Africa	55	55	1000	650	[redacted]
Sweden	18	25	3500	2200	[redacted]
Ukraine	66	72	30000	9000	[redacted]
Venezuela	15	16	4000	2400	[redacted]
Other countries	43	50	11000	6200	[redacted]
World total (rounded)	2240	2400	180000	87000	75

Table 1: Annual mine production and estimated reserves of iron ore, taken from Jorgenson 2011. Figures are in millions of metric tonnes

It would appear straightforward to estimate these in-use stocks, although it turns out the devil, as so often, is in the details. Gerst & Graedel (2008) summarised much of the work done on this subject over the last 70 years and found that, although the first articles were written on the subject in the 1950s and '60s, 70% of all publications have been written since 2000. Indeed, up to that point they found the concept to be "ill-defined", although since then work on material flow analysis and in-use stocks has grown exponentially, presumably bringing improvement.

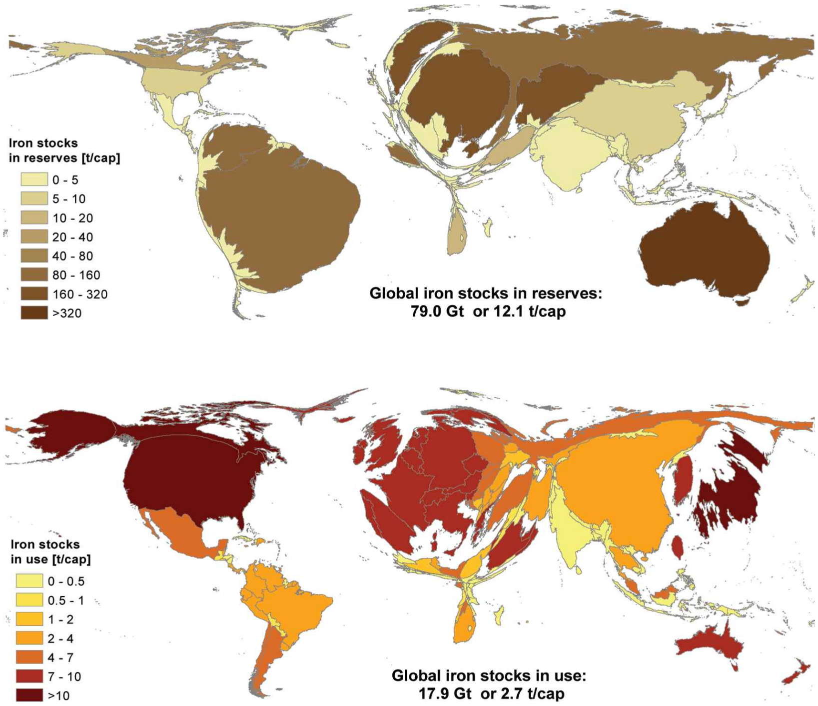

Figure 5: Density-equalizing maps of iron stocks in 2005 showing natural stocks (top) and anthropogenic stocks (below). Country sizes are proportional to their absolute stocks, while the colour scale indicates stocks per capita (from Müller, Wang & Duval 2011)

A macro, top-down methodology for calculating stocks was first proposed by H.F. Bain in 1932, where he simply stated that the stocks at time *t* would simply be the sum of all in-flows minus outflows during that time, plus the original stock at *t=0* (Gerst & Graedel 2008). Having investigated previous studies, Gerst & Graedel (2008) came up with a number of criticisms, including that similar methodologies produced somewhat different results, although none of them included error estimations.

Hatayama et al. (2010) estimated that world steel stock reached 12.7 billion tonnes in 2005, a figure twice that of just 25 years before (a figure slightly lower, although in the same order, as that predicted by Müller, Wang & Duval (2011), shown in the lower part of Figure 5). Much of this growth came from Asia, with in-stock iron and steel increasing 5 times in the 25 years from 1980, while the rest of the world was much more stable. Nevertheless, with such a large population, and after starting from such a low level, Figure 6 shows that per capita, Asia (1.5 tonnes per head) still lags far behind North America, the CIS (which have been estimated to have large stocks from the pre-1990 Soviet era), Europe and Oceania, who all have in-use stocks of over 5 tonnes per capita. Of this world total, construction and buildings account for around 60% of in-use stock due to their longevity (ibid.).

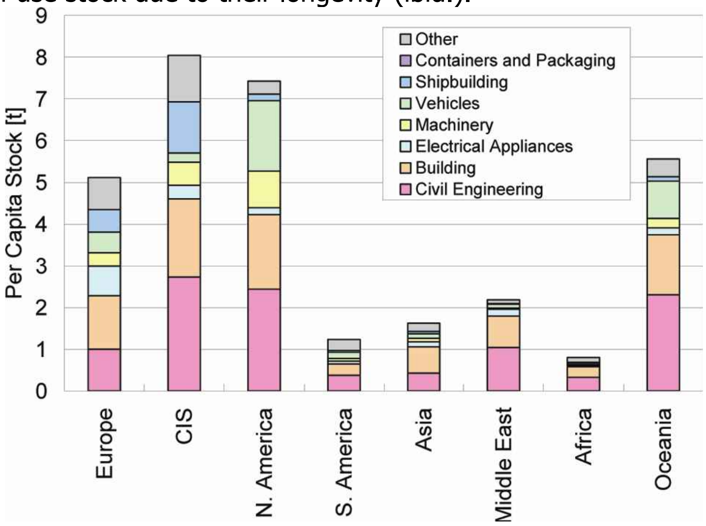

Figure 6: Composition of the in-use stock, as of 2005, by region (from Hatayama et al. 2010)

Patterns of consumption against economic prosperity (GDP) are usually considered to take the inverted U-shaped form of the Environmental Kuznet's Curve (EKC), where the measure of intensity of use is presumed to grow initially, plateau-out and then fall (Hatayama et al. 2010). Apart from there being no empirical evidence of this hypothesis in the case of iron and steel, Müller, Wang & Duval (2011) come up with three further criticisms; first that the relationship is purely statistical, lacking a systems perspective; secondly it presumes resource cycles are driven by production alone, and third that the method lacks robustness because it takes the ratio of two flow variables, which may fluctuate with time.

Instead, from empirical studies, Müller, Wang & Duval (2011) produced Figure 7; a plot of per capita iron stocks against GDP. The resulting curve has a number of interesting implications. It appears that countries require about 2 tonnes of iron per capita in order to begin a period of strong and sustained growth (Pauliuk, Wang & Müller 2012). In a way this is logical because a certain level of infrastructure; roads, railways, factories, ports and airplanes, would be necessary in order to produce further growth in the economy. China entered this phase in 2006, while the US and UK passed the threshold around 1900, France in 1920 and Japan in 1965 (ibid.). After the initial strong growth phase, a plateau phase, implying saturation, can be seen in the USA, UK and France, at a level of around 10 tonnes/capita after GDP/Capita passes US$20,000 (PPP using 1990 Dollars). Japan, Australia and Canada, on the other hand, appear to still be growing, albeit at a slower rate, and should reach 12t/cap in the near future (Müller, Wang & Duval 2011). This plot could be seen as the first half of the EKC, although the data, and logic, would suggest that in-use iron stocks always be necessary for a certain level of development, so saturation could suggest the plateau be a permanent upper threshold.

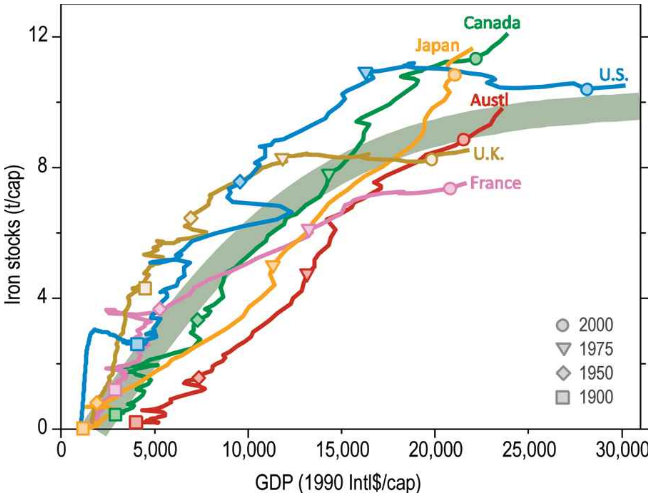

Figure 7: Per capita iron stocks in use versus per capita GDP PPP (1990 international dollars), from Müller, Wang & Duval (2011)

2.3.2 Flows

Apparent Consumption would appear to be the most accurate data available on steel consumption, although it is always less (although normally at around the same ratio) than crude steel production, as shown in Figure 1. Since 2001 global apparent consumption has almost doubled, and the good agreement with an exponential curve is used in Figure 10*: Left* to give a simple prediction for future apparent consumption.

Many studies (Gerst & Graedel 2008; Yellishetty, Ranjith & Tharumarajah 2010) have looked specifically at the flows of iron and steel into the economy, rather than the stocks present. Material Flow Analysis (MFA) uses the concept of conservation of mass to balance all in- and out-flows into a system.

One advantage of this viewpoint is shown in Figure 8. It displays the current dominance of Asia much more clearly than the stocks approach seen in Figure 6. While per capita stocks may still lag behind other regions, in 2005 the continent accounted for over 40% of all in-flows of steel into the global economy, while outflows were around a third of the total, implying a growth in stocks during that year alone of around 200 million tonnes. Of course, these stocks are not evenly distributed amongst the whole population, something Gerst & Graedel (2008) expressed concern over. Within Asia, mean per capita stocks vary from around 9-10 tonnes per head in South Korea and Japan, to 1.8mt per capita in China and just 0.5mt for every person in south Asia (Hatayama et al. 2010). While the differences between MDCs and Less Developed Countries (LDCs) may be considerable, similar distinctions can be drawn between urban and rural populations in LDCs, leading to issues with spatial resolution of these estimates. However, reducing the size of a unit for study, to city or province level, while more precise in some ways, may miss other 'national' infrastructure, such as "ships, large trucks, heavy industrial equipment, offshore drilling equipment, military hardware, and aircraft" (Gerst & Graedel 2008). For this reason it appears that the nation state forms the best, all-be-it imperfect, unit for measurement of stocks and flows. Interestingly, while global stocks were estimated at 60% within construction and buildings, of the in-flows of iron into the global economy only around 45% is for construction, with 24% in transport, 20% in industry and 7% in household durables (Wang, Müller & Graedel 2007), largely due to long lifetimes of constructional steel.

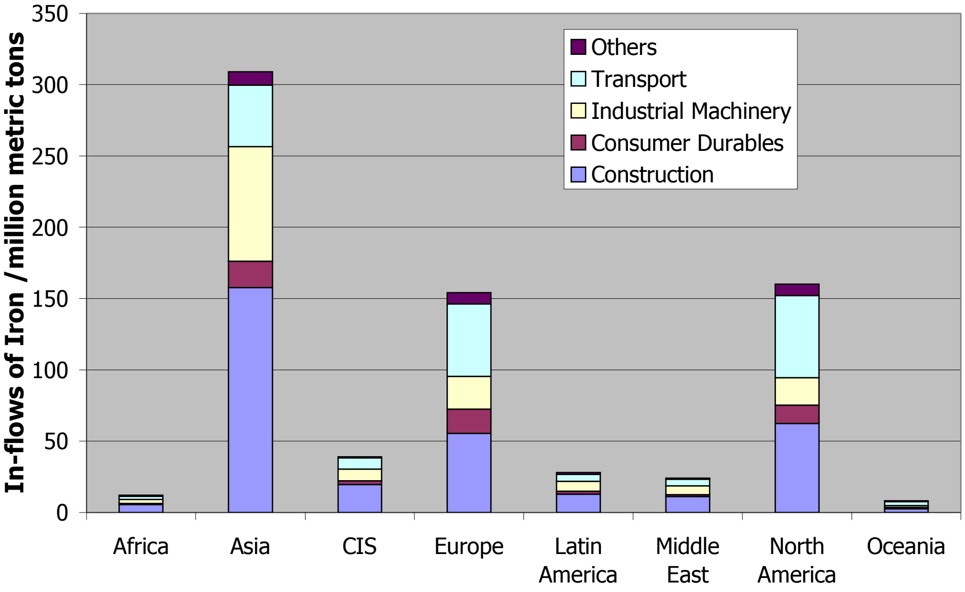

Figure 8: Annual in-flows of iron and steel, by region (data from Wang, Müller & Graedel 2007)

Using annual GDP (PPP) data from the World Bank (2012), a relationship was sought between apparent consumption of steel and GDP. The best correlation found was by plotting the percentage change in annual per capita GDP against annual change of apparent steel consumption for the counties shown in Figure 4. These countries were chosen by considering current GDP and per capita steel consumption (EU, USA and Japan), the so-called *BRIC* group of emerging economies (Brazil, Russia, India and China), large or fast growing steel consumers like Turkey and Indonesia, and the Republic of South Africa was added in order to provide a wider geographical spread.

The plot is shown in Figure 9, and a line of best fit was placed onto the data using excel. The R^2 value of the line was found to be 0.33, which indicates some correlation, and logic would say that steel consumption should change with GDP, although there are evidently more subtleties involved than this simplistic relationship.

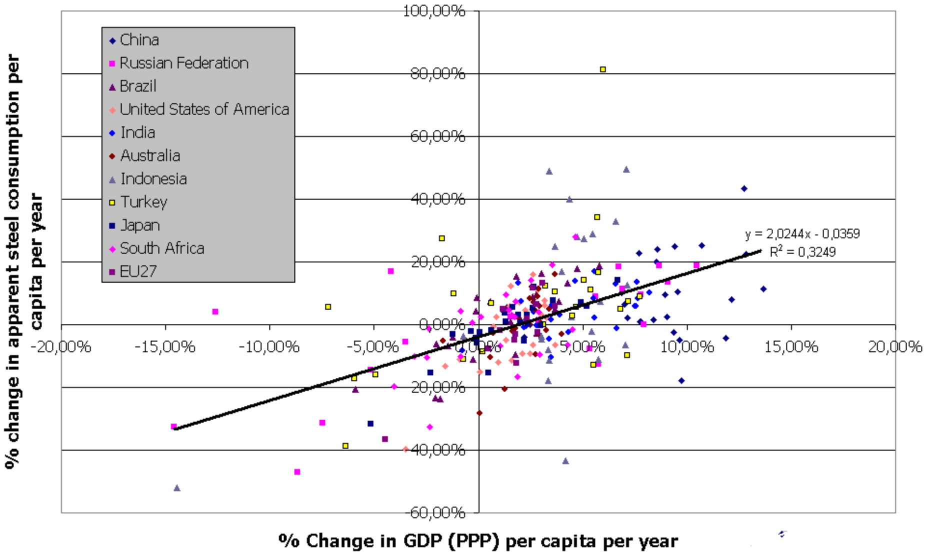

Figure 9: % change in GDP (PPP) per capita per year against % change in apparent steel consumption per capita per year. Data is taken from Worldsteel (2011) and World Bank (2012), for all available years between 1985 and 2010

3. Projections to 2050

In order to understand fully the implications for secondary steel demand to 2050, a number of variables have to be investigated. Firstly, steel demand to that time is projected using a variety of methods and the comparisons allow for testing of the accuracy of projections. Having done that, this section will then turn to supply-side considerations. This involves extrapolation of data on both iron ore production and considerations of scrap uprisings in order to meet the anticipated demand already calculated. The countries chosen were those for which GDP (PPP) projections were available from the EIA (2011). They are the major developed steel producing regions of the world; the EU, Japan, South Korea and the USA. In these forecasts Europe is defined as European members of the OECD, which includes another major producer in Turkey, rather than simply the EU 15, 25 or 27. The so-called *BRIC* countries of Brazil, Russia, India and China were included as they are the countries expected to exhibit significant growth in the near future. Every other country or region was then included in the *Rest of the World* category, which includes developed economies such as Canada and Australia, as well as the poorest; the rest of Asia and Latin America, all of Africa, the Middle East and islands, as well as the non-OECD European countries.

3.1 Steel demand

A variety of methods exist for calculating future steel demand, and can be broken down into either flows or stocks. In the first instance, global apparent consumption is considered and a prediction for future consumption is found. The next subsection then looks at in-use stocks against time and material wealth, and combines a couple of methodologies from the literature to give overall annual steel demand to 2050. In this way, annual in-flow requirements can also be inferred, allowing for Section 3.2 to investigate the requirements for future supply.

3.1.1 Apparent Consumption

A simple test for the following predictions was calculated by fitting an exponential curve to historical apparent consumption data provided by WorldSteel (2011). A reasonable correlation was found with R^2=0.72 (Figure 10*: Left*). This very basic extrapolation was preformed in order to ascertain whether the following calculations from stocks are believable. The significance of global apparent consumption is an interesting one, as there are no imports or exports out of the system, implying global apparent consumption is effectively *real* consumption, although it is normally lower than crude steel production (Figure 1), suggesting either problems with the statistics, losses in the system or stock holding by governments or companies.

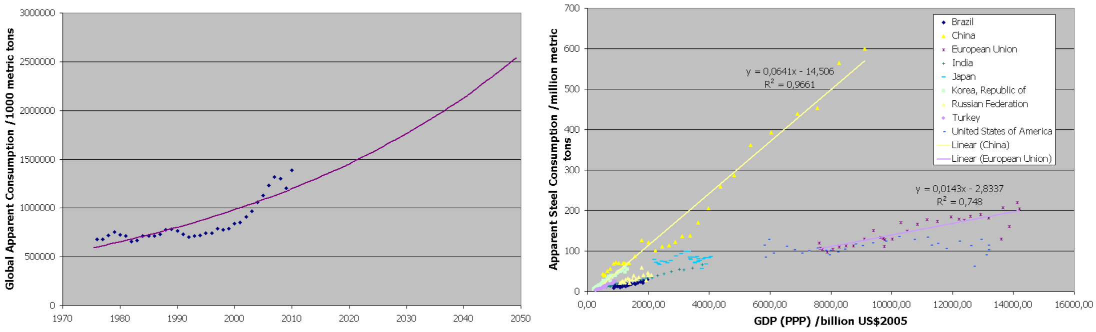

Figure 10: Left; Global Annual Apparent Consumption from 1976 to 2050 (projected) Data from World steel (2011). Right; GDP (PPP) against apparent steel consumption, with two distinct lines of best fit, one for China (yellow) and one for the EU (Purple). Data from World Steel (2011) and World Bank (2012)

The right-hand side graph of *Figure 10* shows two possible relationships between GDP and apparent consumption. Europe, Japan and the USA follow a certain trajectory of low steel consumption to high GDP, while China, South Korea and possibly Turkey exhibit another state of high steel consumption to lower GDP. China and Turkey are both large producers of steel relative to their populations, which could explain that similarity. Interestingly, India and Brazil appear to be following the same course as the highly developed regions. This could be from the cultural influence of colonialism, although is probably due to other factors.

3.1.2 In-stock steel

Müller, Wang & Duval (2011) propose a method for projecting in-use steel stocks by using the so-called Gompertz function as a way of approximating the curve shown in Figure 7. Using Equation 1 below, Figure 11 was produced showing in-use stocks and annual net changes in stock levels (or net inflows to stocks). The per capita stock, S_{PC} is given by the formula

$$S_{PC} = S_{PC}^{L} + (S_{PC}^{U} - S_{PC}^{L})e^{-e^{-b(g-g_0)}}$$

Equation 1

Where S^L_{PC} is the lower limit of per capita stocks (defined, logically, by Müller, Wang & Duval (2011) as *=0*) and S^U_{PC} is the upper limit, or saturation stock level, set at a generous 16 tonnes per capita (according to Figure 7 this level is currently around 10-12 tonnes/capita for the countries studied). *b* is a constant, given the value of 0.000082, *g* is per capita GDP and g_0 is a reference GDP, set to 10100 (PPP 1990US$).

Using Equation 1, projections were made of future in-use stocks across a number of countries and regions, as shown in Figure 11. The right-hand graph is the annual change in stocks, showing net in-flows inferred by the in-use iron stocks graph on the left. The graphs use the medium population projection provided by the United Nations (UN 2004) and GDP (PPP) projections from the US Energy Information Administration (EIA 2011), adjusted to 1990 US dollars, and where the 15 years from 2035 to 2050 are inferred by extrapolating the average growth rates seen in the period 2030-2035.

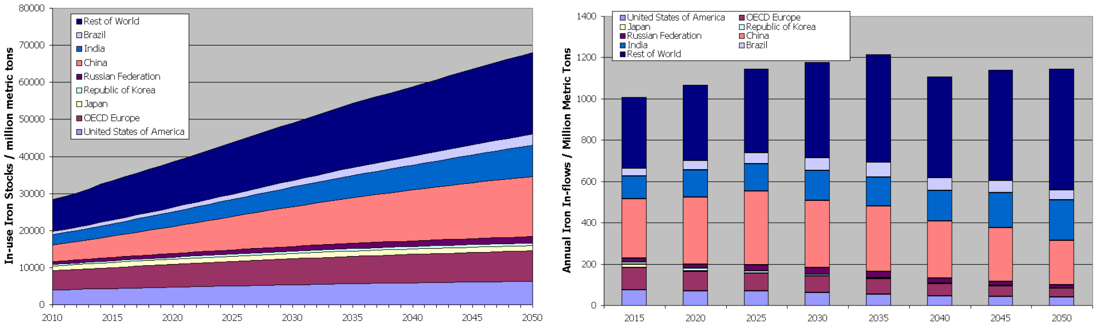

Figure 11: Total Global In-use Iron stocks to 2050 (left) and Annual iron in-flows to the economy (right) using the Gompertz function shown in Equation 1

In-use steel stocks will increase from current levels of just under 30 billion tonnes to nearer 70 billion by 2050. The estimate of current in-use stocks is around a third higher than that made by Müller, Wang & Duval (2011) and shown in Figure 5, and reflects the uncertainties in making these kinds of projections. That said, a doubling of in-use stocks in forty years may be a low estimate when considering recent changes and rather more substantial growth rates. A similar study by Hatayama et al (2010) predicted that current in-use stocks would rise from 2005 levels of under 10 billion tonnes to around 55 billion by 2050, suggesting growth rates higher than those predicted in Figure 11.

3.1.3 Turnover of stock

The right-hand graph of Figure 11 shows the net in-flows of stocks, however in order to make accurate projections, the turnover of stock currently in-use must be considered to give a better idea of future steel demand. Following the work of Hatayama et al (2010), three main categories of stock have been chosen; buildings, civil engineering and vehicles, and the turnover rates from these three categories will be used to make projections. This method should cover 70-80% of all steel in use, and due to long turnover times in both construction and civil engineering it will produce a low estimate of future steel demand.

Dargay, Gately & Sommer (2007) estimate global vehicle ownership to 2030, using a Gompertz function similar to that used by Müller, Wang & Duval (2011) to approximatethe curve shown in Figure 7. They found reasonable agreement across a number of countries, as shown below.

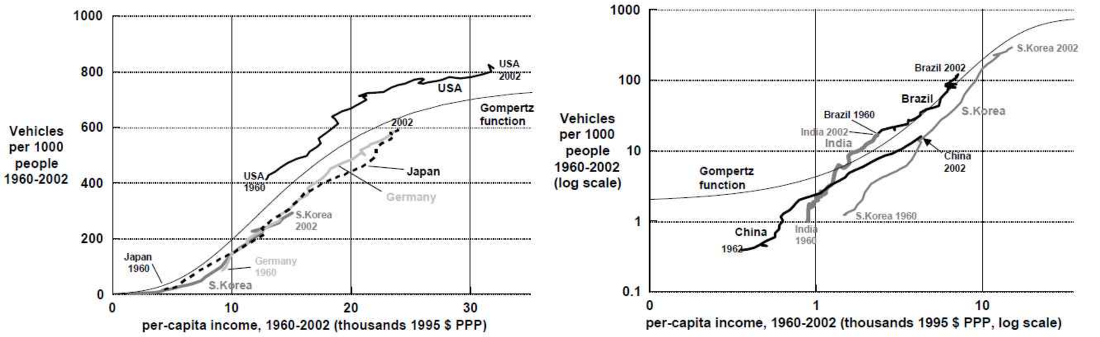

Figure 12: Relationship of vehicles per 1000 people to GDP per capita for Germany, Japan, USA and South Korea (left) and an equivalent log-log graph for India, China and Brazil (right). Graphs from Dargay, Gately & Sommer (2007)

The equation for this Gompertz function is of the form

$$V_{it} = \gamma_{\max}\theta e^{\alpha e^{\beta GDP_t}} + (1-\theta)V_{t-1}$$

Equation 2

Where V_{it} is vehicle ownership (per 1000 people) in country *i* at time *t*. GDP_t is per-capita GDP (PPP) expressed in constant 1990USD (in this case), γ_{max} is the saturation level of cars per 1000 people, θ accounts for the lag in adjustment for vehicle ownership with incomes ($0< \theta <1$) and α and β are negative constants. In order to make the calculation, a couple of simplifications were made to the formula proposed by Dargay, Gately & Sommer (2007). They suggest a method for calculating a dynamic saturation point dependent on population density and urbanisation, which was found to be too complicated for this study, so a constant saturation point was taken for each country from Table 2 of their study (ibid.). Where figures did not exist for OECD Europe as a whole, weighted means were taken of each member state, and summed to give a weighted average for the block. According to the authors, θ should actually have two values, one for positive growth and one for negative. As the statistics used for GDP (EIA 2011) predicted positive year-on year growth for every country or region to 2050, the negative θ was not deemed suitable. However, this is probably more of an issue with the growth projections than the formula.

Having made the calculations for vehicle ownership per 1000 people, it was straightforward to multiply this by projected populations (UN 2004) to find a prediction of absolute growth in vehicle ownership to 2050, as shown in Figure 13. Over the eight countries and blocks studied, a near 350% increase is observed over the timescale of this study, largely driven by growth in India and China. Car ownership in the Rest of the World category used a linear extrapolation of vehicles per capita against average GDP/cap, which is a very blunt tool, but considering the category 'Rest of the World' will, by 2050, account for almost half the world's population (ibid.), the share of less than a third of the world's vehicles seems reasonable. Assuming a car weighs a tonne on average (in the United States this is probably an underestimate, while in India, for example, it may be an overestimate), that would mean in-use stock of steel used in vehicles will reach around 5 billion tonnes by 2050, or around 8% of total steel in-use according to my calculations.

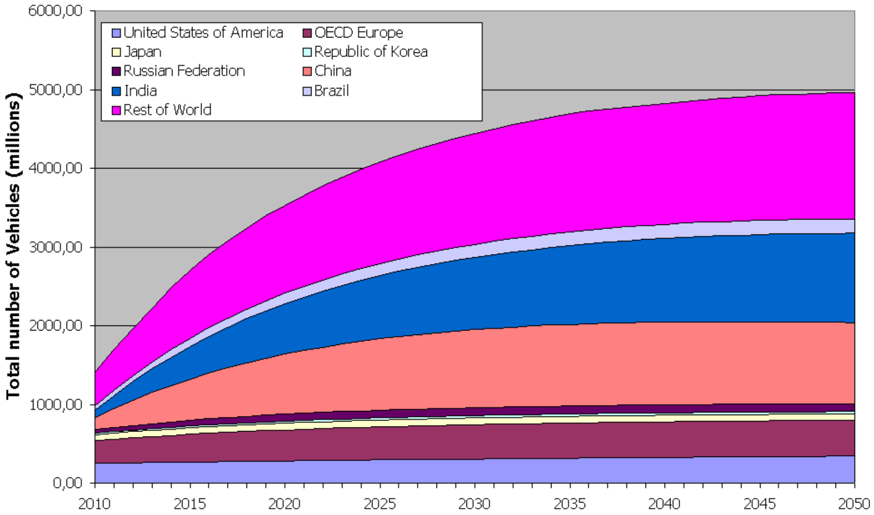

Figure 13: Vehicle Ownership projected to 2050. Method from Dargay, Gately & Sommer (2007)

As there are only three categories to consider, it is assumed that all the steel stock not in use in vehicles will be found in one of the other categories. Hatayama et al (2010) calculated a ratio of the two which was empirically found by considering the population densities in 47 Japanese prefectures, and the relationship was given by the following equation

$$\frac{Con_{CE}}{Con_{const}} \approx 0.191 + 0.419e^{-\left(\frac{PopDensity}{276}\right)}$$

Equation 3

Where Con$_{CE}$ is the Figure 14 shows the break down of in-use steel stocks to 2050 by category. This will then be used to calculate dynamic steel demand as well as scrap uprisings.

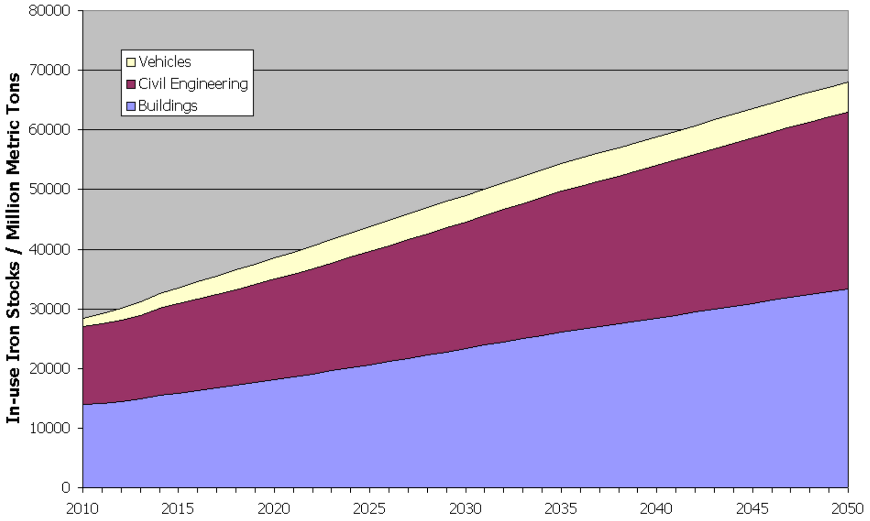

Figure 14: Total In-use iron stocks by category

To convert the above graph of in-use stocks to demand for steel, the average lifetimes of the three categories are used to make the estimate. Both Hatayama et al (2010) and Müller et al (2007) estimate lifetimes for various goods. It was decided to use the figures given by Hatayama et al (2010) as they cover multiple regions, although the standard deviations for those calculations are taken as percentages from Müller et al (2007). It was assumed that when stocks come to the end of their lives, they are replaced like-for-like (i.e. the amount of steel required is the same for the replacement as for the original). The replacement distribution was assumed to be Gaussian, as according to the sensitivity analysis conducted by Müller, Wang & Duval (2011), this is a reasonable approximation. For previous years, the ratio of the three categories was assumed to remain constant between 1945 and 2010, and the amount of steel in-use stock was extrapolated linearly backwards using a ratio of iron stocks to GDP (PPP) at constant 1990USD (taken from UN 2004). Early uprisings of scrap, especially in LDCs, were found to be negligible. The cumulative annual uprisings (shown by the purple bars below) for every year and category were then taken for each country. An example of 10-yearly turnovers of steel used in Chinese vehicles is shown in Figure 15, where the different coloured lines represent all the vehicles (in this case) introduced into an economy in that year, and the curves show the number of those vehicles scrapped and replaced by year. The insignificance of pre-1980 vehicle turnover is obvious from the graph, as would be expected in China.

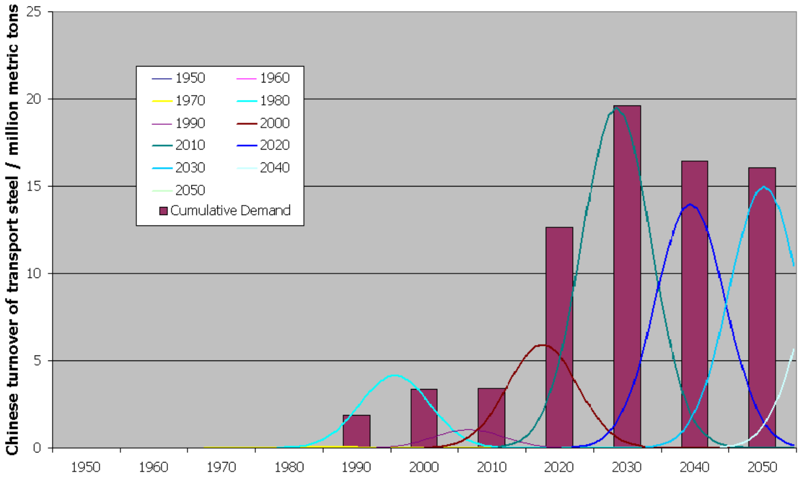

Figure 15: Annual Turnover of Chinese vehicles, with cumulative demand/uprisings shown in the purple blocks

Cumulative demand for replacement items was then added to the required steel in-flows shown in the right-hand graph of Figure 11, and total demand to 2050 was calculated and shown in Figure 16, which displays demand by region (top) and demand by category (bottom). Furthermore, the apparent consumption curve from Figure 10*: Left* has been superimposed onto the top graph to give an idea of the feasibility of these projections. They are higher than extrapolated apparent consumption up to the blip around 2035, when the apparent consumption curve overtakes the plateauing annual steel demand. That said, the magnitude of the two projections are reasonably in agreement.

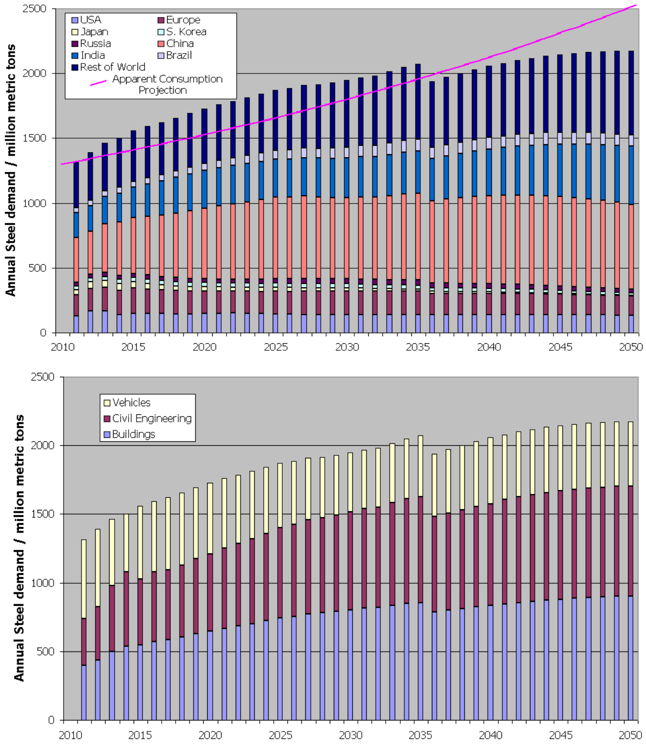

Figure 16: Annual cumulative steel demand to 2050 by country/region (top) and by category (bottom)

China is, of course, the largest single contributor to global steel demand, and this projection shows growth to around 700 million tonnes by 2050, a figure which is higher than that of Pauliuk, Wang & Müller (2012), who estimated demand to be between 340-510 Mt/year by then. However, my study was closer to other estimates, with the IEA predicting demand to be 610-690 Mt/year in 2050, and the China Energy Group at Berkley going further to suggest demand of 850 Mt/year by then (Pauliuk, Wang & Müller 2012).

Starting at around 1.3 billion tonnes of steel demand in 2011, the projections in Figure 16 show a steady increase to around 2035 and continued growth following the blip at that point. The starting level is fairly consistent with the 1.38 billion tonnes apparent consumption of steel in 2010 (World Steel 2011). The anomaly in the curve may come from the method used to project GDP, whereby projections for GDP were only available to 2035 (EIA 2011), and post-2035 projections took the average growth rate of the previous five years and extrapolated forward. However, this kind of dip could also come from an economic downturn, the likes of which are not predicted whatsoever in the GDP projections, so has been left in as an example of the effects a year of negative growth may have on future steel demand.

3.2 Steel Supply

Crude steel production requires input from either secondary steel or iron ore (currently at a ratio of about 1:2). Of the studies which have been performed on steel projections, most assume iron to be abundant and environmentally harmless (Wang, Müller & Graedel 2007; Hatayama et al 2010). Rejecting shortages of iron ore could be due both to the timescales involved in the projections, and in the apparent unreliability of data both on natural and in-use stocks. There are also problems with the concentration of iron in the ores, as a minimum occurance of around 25% is currently considered the economic limit. This could change with increased prices for iron ore, but there still remains the problems that many reserves are either inaccessible (under the ocean, for example) or too dilute ever to be worth the cost of extraction and refining. This section will combine extrapolated forecasts for iron ore production with implied steel scrap requirements to build a dynamic picture of the supply of raw materials for steel making to 2050.

3.2.1 Primary production

In order to assess the possibilities for future steel production from iron ore, historical data from the British Geological Survey (Brown et al 2012), for both annual global pig iron and iron ore production, was plotted and is shown in Figure 17. As Yellishetty, Ranjith & Tharumarajah (2010) point out, the increase in iron ore output is expected to continue exponentially for the "coming future". Therefore exponential curves where fitted to both the plots of iron ore and pig iron production using EXCEL, and the resulting curves both show good correlations to data, with R^2 values of 0.91 for each plot. The two growth curves are represented by equation 4, which takes the form

$$P(t) = Ae^{kt}$$

Equation 4

Where *P(t)* is the amount produced in year *t* and *A* and *k* are both constants. This formula is similar to that proposed by Yellishetty, Ranjith & Tharumarajah (2010), who made similar calculations for data up to 2005. Both constants were found empirically using Excel. In the case of iron ore, $A=4\text{x}10^{-26}$ and $k=0.0329$, while for pig iron production, $A=4\text{x}10^{-27}$ and $k=0.0337$.

As the ferrous content of the ore is unknown, pig iron production for that year gives an estimate of the iron content of the ores. Pig iron has a high Carbon content, typically between 3.5-4.25%, and a significant Silicon content of some 1.25%, meaning that ferrous content of pig iron can be approximated to 95% (Özer, Evcimen & Ekerim 2009). The observed Fe content of iron ore was fairly constant over the life-span of the data, between 50-60%. The linear projection (yellow area) suggests the ratio may increase with time as more iron ore is mined, however that may be counter intuitive as one would expect the richest reserves to be mined first, implying later iron ore mining, driven by increased prices and demand, should have lower yields. This is certainly the case in the United States, where iron ore grades have diminished from a World War 2 level of 50-60%, to around 25-30% today (Müller et al 2006). For the purposes of this study, iron ore is assumed to yield 50% Fe content, regardless of the amount of iron ore produced.

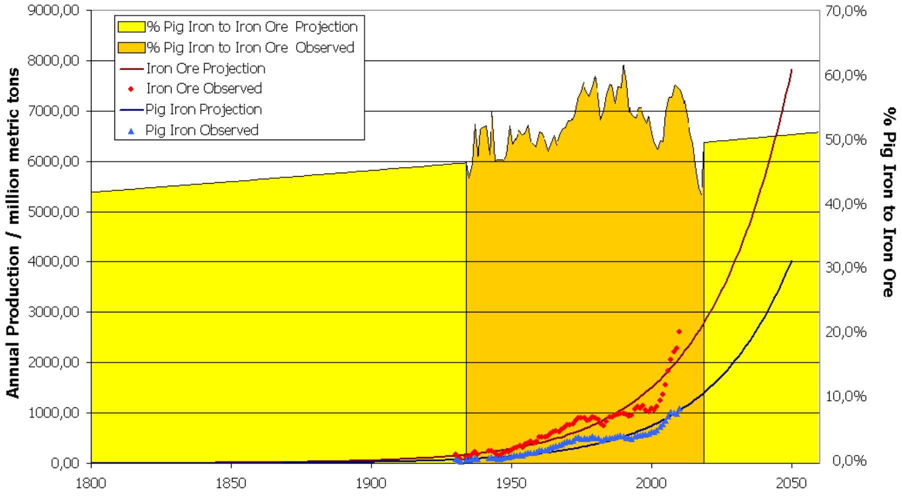

Figure 17: Observed and projected global iron ore extraction and pig iron production (left-hand axis). The yellow/orange areas are the projected/observed annual ratios of pig iron to iron ore production (right-hand axis). Data from Brown et al (2012)

Despite iron making up around 5% of the Earth's crust (Müller et al 2006), much of that stock can be expected to be found at uneconomical concentrations (less than around 20%), or in inaccessible locations as posited above. Therefore it is interesting to consider the limits to the projected exponential growth. Hubbert (1956) was the first to coin the phrase 'peak' resources, and his work shows that an inflection point can be expected in the output of resources when the total remaining reserves available is equal to the amount already extracted, causing a peak in the production of that resource in a certain year, and resulting in a reduction in production. The basic model for this curve is the normal, or Gaussian, distribution curve.

Given that stocks play such an important part in Hubbert's theory, it is necessary to have an estimate of available natural stocks of iron extracted and remaining. Yellishetty, Ranjith & Tharumarajah (2010) point out that many studies have attempted to estimate stocks, but the value of natural stocks chosen for this study was provided by USGS (Jorgenson 2011), as shown in Table 1. The table provides estimates of iron ore reserves by country, and the figure of 87 billion tonnes of iron within 180 billion tonnes of crude ore is fairly consistent with the 50% Fe content of ores estimated above. The total reserves extracted up to time *t*, *Q(t)*, can be estimated simply by taking the sum of all the iron produced up to that point, or

$$Q(t) = \sum_{t=1800}^{t} P(t)$$

Equation 5

Where the first year of calculation is arbitrarily defined as 1800, a time when iron ore extraction was insignificant compared with modern times (as shown in Figure 17).

According to the USGS (Jorgenson 2011), crude ore reserves at *t*=2010 were 180 billion metric tons. The total natural stocks in metric tons, *R(t)*, in year *t*, can therefore be given as

$$R(t) = 180x10^9 + \sum_{t=1800}^{t=2010} P(t) - Q(t)$$

Equation 6

So Hubbert's peak will be found when Equation 5 equals Equation 6, or

$$R(t) = Q(t)$$

where the amount extracted is equal to the available reserves. From here a limit can be put on this exponential growth, and the peak year was calculated as 2028, at a level of over 3500 million tonnes (of iron ore) per year. This compares with a study by Yellishetty, Ranjith & Tharumarajah (2010) which used historical data from 1950-2005 to estimate ore extraction of

2883 Mt a year in 2030, although their exponential plot misses the important and significant production increases seen since 2005, so would be expected to be lower. The peak curve should take the form of a normal Gaussian distribution, however as this curve utilises a different exponential function than that extrapolated above, the bell curve was estimated by drawing a smooth curve (in orange) rather where the sharp peak is found, as shown in Figure 18.

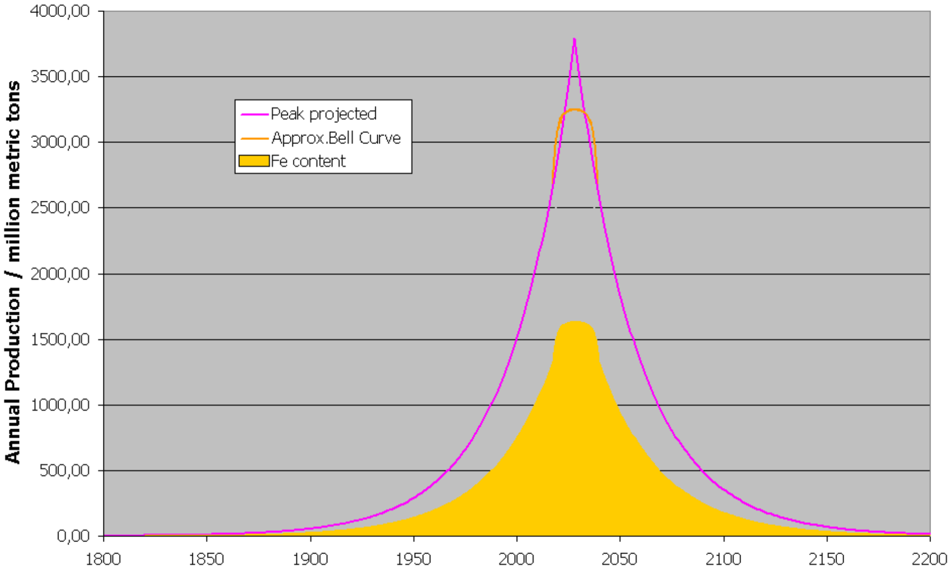

Figure 18: Projected iron production in accordance with Hubbert's peak theory, including the exponential peak (in pink), an approximate normal curve (orange) and an estimated ferrous content of that iron ore

This projection can be superimposed onto Figure 16 to investigate the possibilities for iron to supply the increased steel demand up to 2050. The result is shown in Figure 19, using the exponential peak rather than the smooth curve. According to the graph, up to around 2035 iron ore can supply much of the required input for steel. Indeed, should iron ore production continue along the current path, around 2025 mined iron will likely exceed demand. During this time, sufficient reserves must be kept to ensure the transition to a more scrap-dependent economy is possible. By 2050, iron ore will only be able to provide half the necessary iron for steel production, implying a much more important role for scrap steel. This situation is defined as Scenario 1.

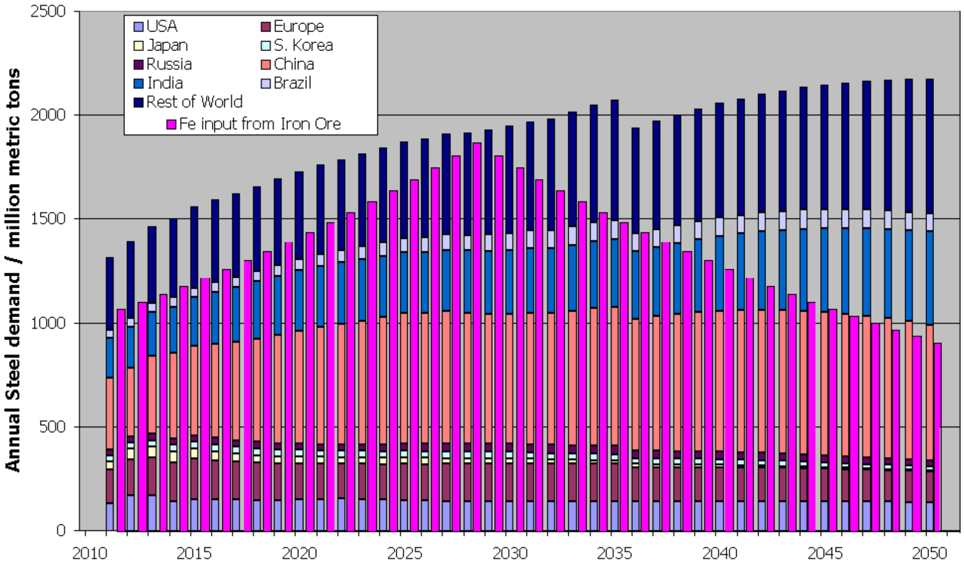

Figure 19: Scenario 1 - Global iron supply from ores (in pink) against regional demand for steel

Figure 19 assumes that supply of iron ore is independent of demand, which is a possibility should financial speculation, for example, be a major driver in iron ore production. However, as that does not currently appear to be the case, one further projection was made assuming that iron from ores contributes two-thirds of total iron supply (the approximate current ratio of BOF to EAF production) until it peaks, when the same exponential fall-off could be expected. Figure 20 (depicting Scenario 2) shows the expected relationship between supply of iron from ores and recycled steel requirements to fulfil the demand projected in Figure 16. The peak of iron ore production has now moved to the early 2040s, from where it falls off exponentially and afterwards requires a greater contribution from secondary steel – about a half (1 billion tonnes) by 2050. Scrap requirements and uprisings are discussed further in the next section.

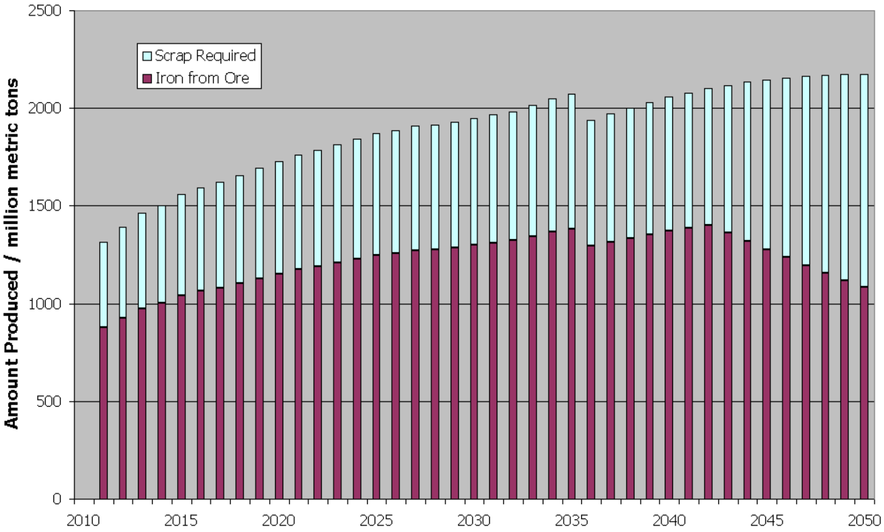

Figure 20: Scenario 2, showing contributions from iron ore and secondary steel in fulfilling demand to 2050, assuming iron from ores contributes two thirds of the supply until peak iron, now in 2042

3.2.2 Recycling

Regardless of whether iron ore production does peak in 2028 or 2042, secondary steel will play an important role in future steel supply because of energy and emissions considerations. Figure 21 plots the global requirements of scrap steel from 2011 to 2050. In both scenarios the level of about 300-400 million metric tonnes required in 2011 is of the order of today's scrap uprisings, but interestingly, as we approach peak iron in scenario 1 the scrap content of steel will decrease. Of course, this is not necessarily the case, and it would be expected that scrap will continue its influence on steel production due to economic considerations, if nothing else; a situation better shown in the right-hand graph (Scenario 2) of Figure 21. The peak in iron ore is longer in coming and appears less severe than in scenario 1, although overall scrap requirements will continue to increase up to the early 2040s at a variable year-on-year rate of between 5-0.5% (average 2%) up to the blip at 2035, before exponential growth averaging almost 6% a year is seen following the peak in iron ore production in 2042. In 2050 therefore, required steel production from scrap will be 1.25 billion tonnes (Scenario 1) or 1.1 billion tonnes (Scenario 2).

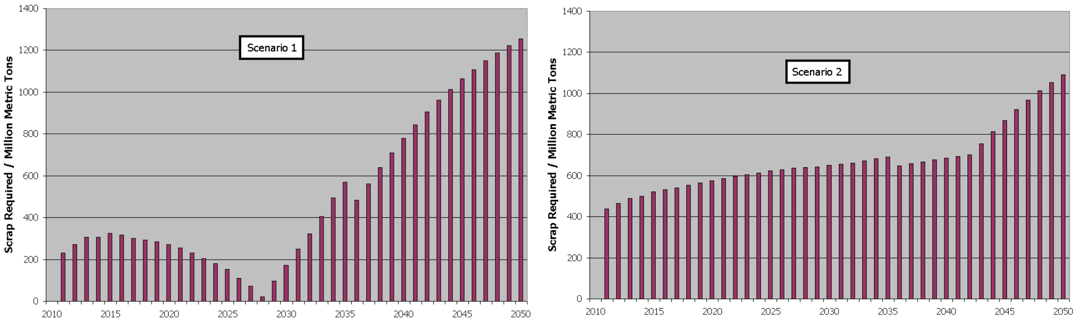

Figure 21: Left; Annual secondary steel requirements assuming the situation depicted in Figure 19 and Right; annual scrap requirements to meet the scenario shown in Figure 20

Having a reasonable understand of steel scrap requirements to 2050, we now turn to consider the uprisings of scrap steel available for recycling during that period. The steel turnover method outlined in Section 3.1.3 doesn't just predict the amount of new demand to replace old stocks; it also gives a measure of the scrap that will be made available at the same time. Assuming no losses and 100% recycling, Figure 22 estimates the amount of steel available for recycling up to 2050, both by region and by category, independent of either of the scenarios depicted above, while the green line shows scrap uprisings as a percentage of total steel production/demand in that year. The plot displays an s-shaped curve, where growth rates slow in the late 2020s (around peak iron in scenario 1) accelerate again to 2045 and then slow once more. This is due to the various lifetimes of in-use stock. While this is very much a top-down method, the type of scrap uprisings should not go unmentioned. In this model, vehicles make up a large amount of recoverable scrap, mainly due to their shorter lifetimes (between 13-20 years, depending on the region) when compared with construction. However, as any scrap metal dealer will tell you, the quality of car scrap is normally much lower, with associated lower yields, than construction scrap. One way to improve the yield is to process the scrap in shredding and separation units, which run into tens of millions of dollars and so are not available to the smaller independent scrap processors.

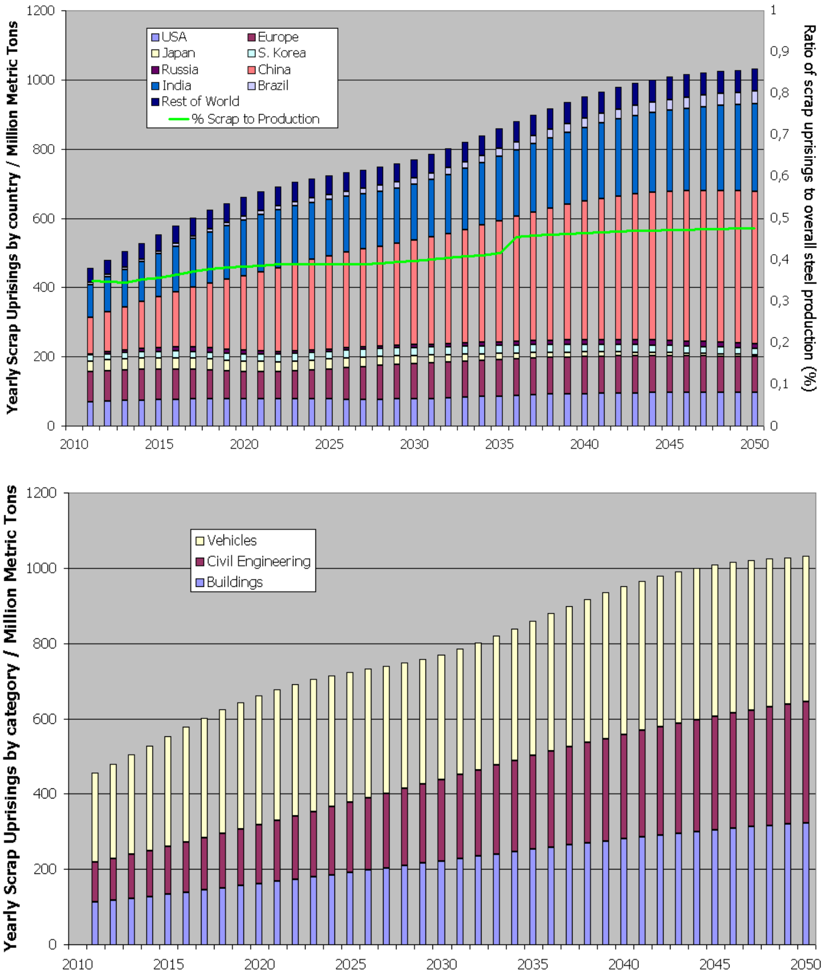

Figure 22: Annual projected scrap steel uprisings by country/region (top) and by category (bottom)

Comparing scrap uprisings with Figure 21 produces another interesting result. According to Scenario 1, in the year 2050 the amount of scrap required to fill the gap between demand and iron ore supply is some 1.25 billion tonnes, although the uprisings in that year (assuming 100% recovery) are only projected to be just over 1 billion tonnes, which would leave a substantial shortfall in the five years up to (and presumably following) 2050. In the meantime, Scenario 2 would require less scrap by the end of this projection, but in the year 2050 scrap requirements and uprisings will be fairly even, although a disparity may occur in later years, should the rate of increase required continue. It should be stressed here that these uprisings assume 100% recycling rate without losses, whereas the best current performance in scrap recovery is seen in the United States, where they average around 80% (in LDCs this total is significantly less than that). As Müller et al (2006) point out, a “significant portion of the obsolete products leaving use does not reach scrap processing and waste management”, with the largest losses coming from discard to landfills (about 16% of US steel is lost this way) and tailings (12% of the annual 1.25 billion tonnes consumed in the US, although some of this would also be recycled as primary scrap) (ibid.).

Compared with other studies, Hatayama et al. (2010) project scrap uprisings to rise exponentially to 2050, from a level of under 200 million tonnes in 2005 to over 1400 in 2050, with the vast majority coming from Asia. This is a much greater projected growth than seen in this study, and both the low initial level and such rapid growth do not necessarily reflect real (or anticipated) world conditions. Meanwhile, Pauliuk, Wang & Müller (2012) show that in China, scrap uprisings will exceed 50% of steel production somewhere between 2025 and 2035, and they estimate that in China, scrap uprisings will surpass steel production/demand by 2050. This is not shown in these results, where the green line in the upper graph of Figure 22 suggests global scrap uprisings will only be approaching 50% of total steel demand by 2050. This discrepancy is probably due to limitations in the three categories selected as the major contributors to stocks, where lifetimes of buildings and civil engineering are so long that they will not produce the required amount of scrap, although the quality of that scrap is likely to be the best available.

3.2.3 Infrastructure Requirements

Currently, crude steel production from EAFs contributes only around a third of total global steel production (World Steel 2011; as shown in Figure 2 of this report). While, in both scenarios, this ratio would be a sufficient up until the late 2030s or early 2040s, after then the scrap to ore ratio required is much higher – 50% or more by 2050. Further to that, although the ratio may remain the same (or less, according to Scenario 1), the increase in crude steel production to over 2 billion tonnes per year in 2035, an amount which Manser (2011) predicts will easily be accounted for in current planned infrastructure (as shown in Figure 1) would equate to a rather higher *absolute* requirement for scrap.

Yellishetty, Ranjith & Tharumarajah (2010) extrapolated current steel production capacity to 2030 using exponential curves with good fits for both EAF and BOF production. Their estimate of over 6 billion tonnes combined installed capacity by 2030 is rather large compared with just 2 billion metric tons annual steel demand projected in this report (shown above); although by that point they do predict EAF capacity to be greater than combined BOF capacity. Price & Danjczek (2011) show that increased EAF facilities are already on the table in Turkey, where they plan to add 8.8 million tonnes capacity by 2015, and Russia, where the 6 million tonnes of new capacity will most likely absorb virtually all of Russia’s current scrap exports (ibid.). What is more, it should be remembered that BOF can take between 10-35% scrap content as feed stock, ostensibly to reduce the temperature of the molten iron (Yellishetty, Ranjith & Tharumarajah 2010; Steel Recycling Institute 2009), so capacity for recycled steel should not be an issue.

Indeed, increasing the supply of scrap may be most challenging part of future infrastructure requirements. China, for example, is already planning to increase the share of scrap in crude steel to 20%, representing an extra 30 million tonnes of scrap consumed per year (Price & Danjczek 2011). It is vital that LDCs increase their scrap recovery, because the developed economies of Japan, the USA and Europe will experience slow growth (and therefore ever smaller uprisings) and have relatively well-developed scrap recovery networks which leave less room for expansion. Furthermore, as scrap increasingly becomes seen as an strategic resource, the international supply of scrap may well dry up. International trade in secondary metals (judged by export data from World Steel 2011) has plateau-ed in recent years after a significant increase in the early years of the 2000s, and today more than 20 countries have restrictions or tariffs on scrap exports. In China, that tax on scrap exports runs to 40%, while in Russia it is more like 15% (Price & Danjczek 2011).

Recycling networks, even in a highly profitable industry like secondary metals, take a long time to bring on line, and in that way many countries may be helped by the apparent abundance of iron ore – up to a point at least. However, as stated above, scrap recovery is not merely a question of raw materials; there are also environmental and economic reasons for increasing scrap content of crude steel which should be considered in medium- to long-term governmental planning, whereby creation of efficient steel recycling networks should be (and often already is) a major priority.

4. Results

These results have been already been described in various sections above, but are collated here to provide easy access to them.

Future steel demand was found by extrapolating the relationship of GDP/Capita (PPP, constant 1990 USD) against steel in-use stocks as plotted by Müller, Wang & Duval (2011) and shown in Figure 7. The relationship was approximated by a Gompertz function, and the resultant projection is shown in Figure 10*: Left*. The annual net change in steel stocks is shown in the right-hand graph of the same figure, and this was added to the demand for like-for-like replacement of three main categories of steel use – vehicles, buildings and civil engineering – to give an overall picture of global steel demand to 2050. Steel demand is projected to rise from current levels of around 1.5 billion tonnes a year to 2.2 billion by 2050 (shown in Figure 16 by region (top) and category (bottom)). Fair agreement can be seen between these forecasts and those made by a simple exponential extrapolation of apparent steel consumption. The increase is steady, with a minor drop, as if from a recession, in 2036. This has been included as none of the annual growth forecasts used (EIA 2011) predicted a single year of negative growth for the next 40 years – a projection which looks even more ridiculous given current economic strife.

Having considered steel demand, supply was then investigated. Supply of feedstock for crude steel production comes from one of two routes, through refined iron ore (the intermediary stage is known as pig iron) or through scrap steel. Plotting historic iron ore extraction against pig iron production (Figure 17) gave a ferrous content of iron ore of around 50%, which is comparable with the estimates of the US Geological Survey (USGS) shown in Table 1. Using the data for reserves shown in the same table combined with Hubbert's Peak Theory of Resource Use, peak iron ore extraction was predicted for either 2028, by assuming growth in iron ore extraction to be independent of steel demand (Scenario 1), or for 2041 by restricting the growth of iron ore production to continue to provide along the approximate current ratio of two thirds of total required Fe content of steel (Scenario 2). After both of these peaks the extraction/production rate fell off exponentially, so that in 2050 scrap steel requirement was either 1.25 and 1.1 million metric tons a year (shown in Figure 21).

Finally, scrap uprisings were considered in order to fulfill this demand. Figure 21 shows the scrap requirements according to the two scenarios, while *Figure 22* gives the annual projected availability of scrap by country/region and by category of scrap, independent of the two scenarios. The uprisings were a maximum limit assuming 100% recovery without losses, although even then scrap uprisings were found to be insufficient to fulfill demand from the year 2040 onwards (Scenario 1) and after around 2049 for Scenario 2.

5. Discussion

Making projections - even into the near future - is always problematic, although attempting to predict consumption patterns 40 years into the future is beset by even more uncertainties. Therefore, what is presented above is in a way a business as usual scenario using relationships which have been developed in accordance with historical data. Much of the report is based on the relationship between in-use stocks and GDP pre capita proposed by Müller, Wang & Duval (2011) and shown in Figure 7*.* It is assumed that future relationships between these variables is true both for all countries and for the foreseeable future, although the upper limit (or in-stock saturation point) used in the equations is a rather higher 16 tonnes per capita.

Nevertheless, the predictions made in this report find reasonable agreement with other projections, not least the exponential growth extrapolated for apparent consumption detailed in Figure 10: *Left*. Those projections made by Hatayama et al. (2010) are similar to those made in this report, although they start and finish with lower overall demand they exhibit a higher rate of growth than set out here. Furthermore, actual current demand (determined by apparent consumption figures from WorldSteel 2011) is more similar to that modelled here than in their report.

While it has been stated above that most projections consider iron ore to be an abundant resource for the foreseeable future, this report attempts to buck the trend by applying Hubbert's Peak theory. The biggest limitations here are the (unquantified) uncertainties in reserves, both in-use and natural. While the estimates for reserves vary hugely between reports, virgin stocks are taken from the well-respected USGS (Jorgenson 2011), which could be considered the most respected estimate. A 2028 peak in iron ore production sounds unfeasible at first, and indeed Scenario 2 (peak in 2041) may be more reasonable in this matter, but it also highlights the dangers in assuming peak production as being unforeseeable. That said, it is interesting to consider how appropriate Hubbert's Peak theory may be in the context of a recyclable/reusable material, when it was originally formulated (and later proven accurate) for non-renewable oil reserves in Texas.

Accounting for the implied demand for secondary steel presents its own issues. The estimates of scrap uprisings shown in Figure 22 are both optimistic, in that they assume an impossible 100% recycling rate; and pessimistic due to the probable greater uprisings which would occur from including other products than simply the 3 categories (buildings, civil engineering and vehicles) used here. This would be due to more rapid turnover of steel used in appliances and machinery than in construction (lifetimes of around 10-20 years instead of up to 75, as is the case for construction in the Americas). However, a faster turnover of goods would also mean higher demand, so by no means is a solution to the projected shortfalls in scrap supply seen in both Scenarios.

There are two further issues with this report. Firstly the growth forecasts taken from the EIA (2011) predict positive annual growth for every year all the way to 2050. As already noted above this is highly unrealistic, especially given the current economic slowdown being experienced in much of the developed world. A medium-sized global recession is modelled above to take place in the year 2036 as a counter-weight to this specific problem. Secondly, as discussed in Section 2.3.2, the resolution of the individual prediction in this report may not be exact enough. Substantial differences between urban and rural populations in very large developing countries like China and India make macro-scale top-down approaches relating average incomes (GDP/Capita) to steel stocks rather problematic. However, as noted above, a smaller resolution may disclude such in-use steel stocks as ships, ports, airplanes and other transport which does not exist purely at a city or provincial level. While imperfect, therefore, the nation state most likely remains the best unit for this type of investigation. In order to improve this report, however, more countries should be investigated, because by 2050 the category Rest of the World will count for around 50% of the world's population, and linear extrapolations based on average GDP/capita are not really sufficient for this highly varied percentage of the population.

5. Implications

The major result of this study is that iron ore should not be approximated as indefinitely abundant, and that otherwise unforeseen supply issues may occur as a consequence. The implication of this is simple. Unless governments, especially but not exclusively in less developed countries, plan and implement effective recycling infrastructure there will be problems in supplying the feed stock for making crude steel. While the actual production facilities, either BOF, EAF or otherwise, will probably exist to cope with demand of over 2 billion tonnes a year, this lack of primary supply could cause global economic chaos were it to become a reality. Scrap supply will become more constrained as countries increasingly see scrap steel as a strategic resource and impose export restrictions, so it will fall upon the major steel producing nations to increase domestic recycling rates in order to keep their furnaces supplied. This is especially true in scrap-import-driven countries like Turkey, which currently rely on tens of millions of tonnes of scrap imports a year to supply their EAFs. On the positive side, however, there will be a much higher amount of scrap produced in the inflated global economy of 2050, so governments and businesses will have greater options for scrap recovery in what will surely be a highly profitable business for as long as steel is made.

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