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Long-term production, energy consumption and CO_2 emission scenarios for the worldwide iron and steel industry

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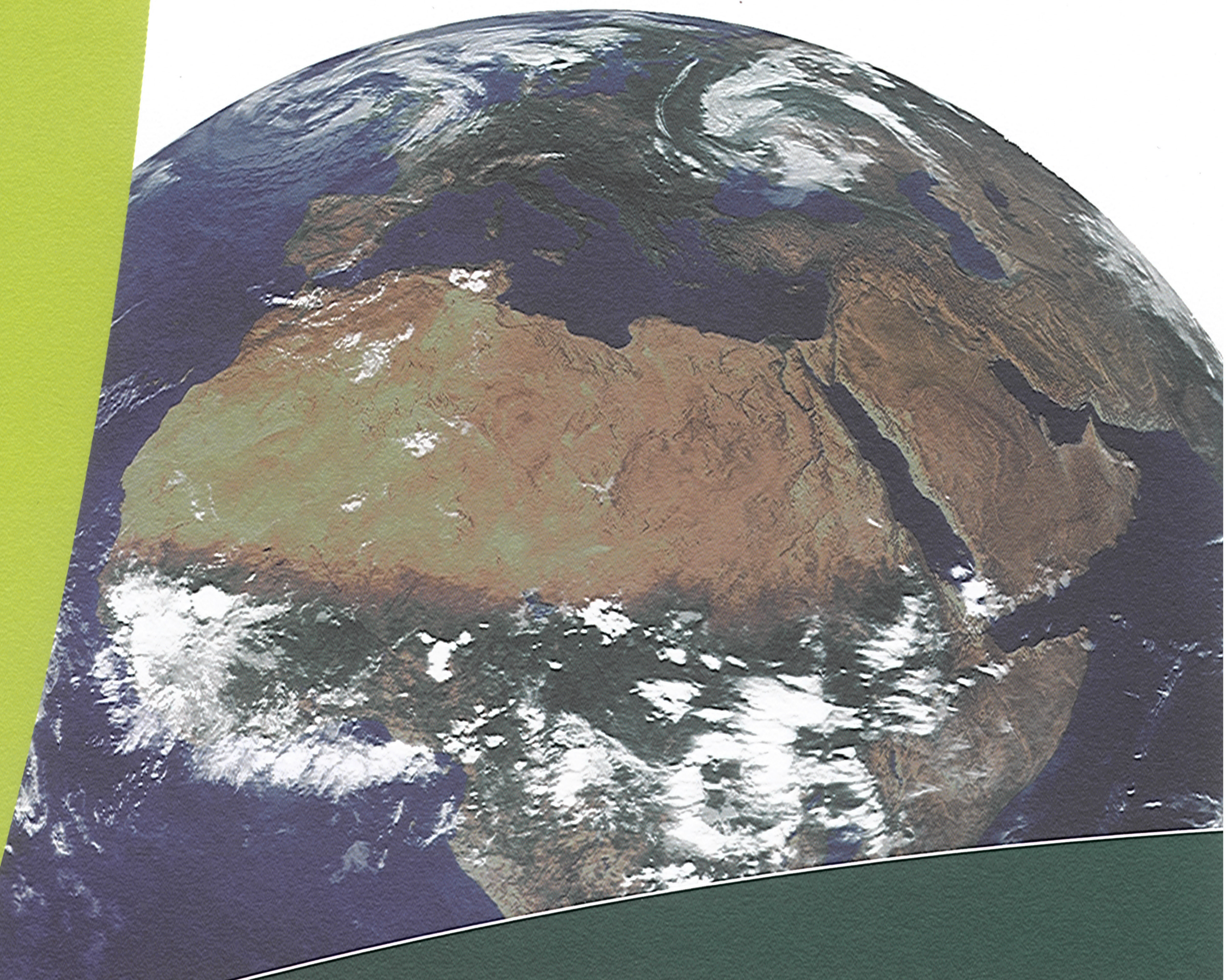

Universiteit Utrecht

This study is contracted by the Netherlands' Environment Assessment Agency (MNP) to the Copernicus Institute for Sustainable Development and Innovation, department of Science, Technology and Society.

Report NWS-E-2006-180
ISBN 90-8672-017-X

November 2006

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Summary

The Netherlands' Environment Assessment Agency (MNP) would like to include in The IMage Energy Regional (TIMER) model physical indicators of activity as driver of energy demand instead of the economic activity indicators that are currently used. In this study we explored the possibility of using physical indicators as driver of energy demand by developing scenarios for the iron and steel industry until 2100.

We projected the demand for crude steel in the 26 TIMER regions using an intensity of use approach that projects per capita crude steel consumption as function of per capita income. In the equation used, per capita consumption grows fast at low-income levels and saturates at high-income levels. We included a time-dependent factor to account for material efficiency improvements as a result of technological progress. Based on an analysis of historical data, we estimate future material efficiency improvements at 0.65% per year. As a result, the per capita saturation level as high-income levels drops from 635 kg per capita in 2003 to 474 kg per capita in 2100 in the basic intensity of use equation used. Using exogenous projections for GDP and population developments according to the four 4 main IPCC SRES scenario groups, this approach results in a worldwide steel consumption of 2000 – 2400 Mt in 2050 and 1900 – 2500 Mt in 2100, depending on the GDP and population scenario chosen. This corresponds to average worldwide per capita consumption levels ranging between 200 and 300 kg per capita. For comparison, worldwide crude steel consumption in 2004 was 1058 Mt, corresponding to an average per capita consumption of 160 kg. In three of the four scenarios, steel consumption reaches a peak somewhere between 2050 and 2100.

In the model, steel production per region is derived from steel consumption assuming as default a frozen trade assumption (i.e. absolute trade flows are frozen to 2003 levels). Rather than exogenously assuming shares of primary (from iron ore) and secondary (from scrap) production technologies, we included a detailed material flow model that determines the future availability of scrap based on past steel consumption in four steel product categories in combination with a lifetime distribution for these product categories. This scrap availability, in combination with a scrap recovery rate, determines the amount of steel that will be produced from scrap. Application of the material flow model to past steel consumption made it possible to estimate the recovery rate of obsolete scrap in the past. For the larger developed regions (USA, Western Europe, Japan), current obsolete scrap recovery rates estimated with the material flow model range between 60 and 80%, which is line with the few other estimates that could be found in literature. For the future, we use as default an obsolete scrap recovery rate of 70%. Based on these assumptions, we project the worldwide share of secondary inputs into steel production to increase from the current 42% to 60 – 70% in 2100 (depending on the scenario chosen). The material flow model also allows estimating the stock of iron products in use and the total stock of non-recovered dissipated steel. The current average worldwide per capita stock of products in use is estimated at 2 ton per capita and is projected to increase to 5.5 – 10 ton per capita in 2100, depending on the scenario.

Energy use and CO_2 emissions are calculated in the model based on the development of the best practice specific energy consumption for the three steel production technologies distinguished (pig iron with basic oxygen furnace, scrap with electric arc furnace and direct reduced iron with electric arc furnace). We assume the best practice specific energy consumption level to decline by 30% until 2100 compared to 1990 levels. For each of the regions, we estimated the energy efficiency levels compared to the best practice in 1990 and assumed convergence to the best practice energy level in 2050 for all the regions. Using this approach, we project worldwide primary energy consumption for the production of iron and steel at 29 – 35 EJ in 2050 and 18 – 26 EJ in 2100 (2004 primary energy use is estimated at 22 EJ). As a result of energy efficiency developments and the increased share of steel

produced from scrap, energy use in all scenarios already peaks before 2050. CO_2 emissions from iron and steel production are estimated at 2200-2700 Mt in 2050 and 1200 – 1900 in 2100.

We explored the sensitivity of the model results to some of the key model assumptions such as the assumed material efficiency factor, obsolete scrap recovery rate and energy efficiency developments. We also explored other assumptions regarding international steel trade and found that different trade assumptions would change the results at the regional level substantially. The sensitivity analyses show that the results of this kind of long-term projection are very much influenced by the basic assumptions made and that the model results should always be interpreted having these basic assumptions in mind. In the final chapter, we discuss various possible improvements of the model such as the inclusion of a production cost based trade module, a more detailed energy and CO_2 module including technologies such as carbon capture and storage and the extension with other materials.

Table of Content

1 Introduction

Developing scenarios on future energy use and CO_2 emissions is important to provide a basis for developing policies for global environmental problems such as climate change. Given the time-horizon of these challenges, not only short (< 5 years) and mid-range (5-25 years) projections and scenarios are required, but also long-term (>25 years) scenarios and projections. The IMage Energy Regional (TIMER) simulation model developed by the Netherlands' Environmental Assessment Agency (MNP) provides an integrated modelling framework to explore long-term future energy use and energy related emissions at a regional level (de Vries et al., 2001). Recently, the TIMER model has been extended from a 17-region model to a 26-region model (Appendix 1).

Energy use in the TIMER model is modelled at an aggregated level. Projections for economic drivers of change (Gross Domestic Product, Value added of services and industry, Private consumption of households) are used as input parameters. These drivers are coupled with an energy intensity indicator for each of five main sectors (industry, transport, residential sector, services and other) resulting in an estimate of total energy use. In a next step, energy demand is fulfilled by different secondary and primary fuels. On the basis of fuel consumption, emissions of greenhouse gasses and air pollutants can be calculated[1].

The MNP would like to include indicators of physical activities at an intermediate aggregation level as drivers of energy demand into TIMER such as person kilometres for the transport sector or floor area for the services sector. The reason is that these physical indicators can help to explain the projected energy use better in terms of changes and also allow a better assessment of opportunities for change[2].

In this study, we explore the possibilities of using physical indicators as driver of energy demand by developing long-term scenarios for the iron and steel industry, one of the most important sub sectors of industry from an energy and CO_2 perspective. The iron and steel sector emitted 26% of total industrial CO_2 emissions in 2003 (IEA, 2006). Specifically, we aim to answer to the following research questions:

Which crucial factors determine 21st century steel use and related energy consumption – and how can changes in these factors be modelled?

Secondly, how can this model be used to explore long-term (up to 2100) scenarios for the consumption and production of steel in the various regions of the world and for the associated energy use and CO_2 emissions?

In the development of scenarios for individual materials (in this case steel) one needs to find an answer to two interlinked questions:

[1] This is a simplified representation of the energy demand model of TIMER. In reality, effects of autonomous and price induced energy efficiency improvements, fuel substitution effects etc. are part of the model. For a detailed description, we refer to de Vries et al. (2001).
[2] With an economic growth of 2% year, a country with a per capita income of 20,000 US$ in 2000 will have a per capita income of 145,000 US$ in 2100. Without any additional physical indicators, it is difficult to understand what such a per capita income means in terms of what we observe in the world around us. Physical indicators (e.g. material consumption) can help to relate economic growth (or better: growth of wealth) to variables having more explanatory power. This does, however, not mean that the relation between the growth of wealth and the development of certain physical indicators is straightforward to determine as will be shown later on.

1. How will the demand for materials develop over time, driven by factors such as economic growth and population?
2. How much energy use and CO_2 emissions will this result in?

In case of a more regional scope of study (as is the case in the TIMER model), an additional question is that of inter-regional material trade:

3. How does the regional demand for materials relate to the regional production of these materials?

We can conceptualise these questions by drawing a chain leading from the key macro-economic driving forces (population and income) via the demand of material functions to material demand, energy use and CO_2 emissions and by relating some relevant conceptual issues to this chain (Figure 1-1).

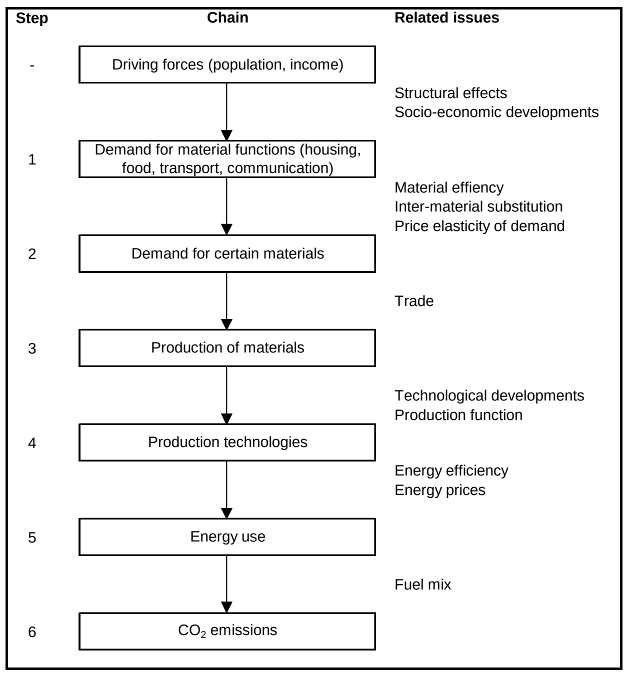

Figure 1-1 Conceptual overview material and energy demand modelling

We will use Figure 1-1 as a conceptual framework to develop a model, which allows us to answer the research question. After giving a brief introduction to the iron and steel industry (Chapter 2), we discuss the various steps given in Figure 1-1 in the three following chapters:

Chapter 3: Steel demand (Step 1 and 2)
Chapter 4: Steel production and trade flows (Step 3 and 4)
Chapter 5: Energy use and CO_2 emissions (Step 5 and 6)

In each of the three chapters, we:

- Give a brief overview of conceptual modelling approaches, including a review of existing studies (Section 1).
- Describe in general terms our own modelling approach (Section 2).

- Analyse past trends in the iron and steel industry and provide relevant literature information required for the exogenous model parameters (Section 3).
- Derive the exogenous model parameters based on these past trends and discuss the modelling approach in more detail (Section 4).

In Chapter 6, we discuss results from some endogenous modelled historical model results (e.g. the stock of products in use and the energy use and CO_2 emissions) and compare these results with available literature sources. In Chapter 7, we answer the research question by using the model for scenario projections for the iron and steel industry.

Although the model was developed for the iron and steel industry, we would like to emphasise that the use of (some of) the model parts is not limited to the iron and steel only. This also holds for the discussion of conceptual modelling approaches for the various steps given in Figure 1-1.

In Chapter 8, we therefore broaden the scope of our study somewhat and summarise on a more conceptual level directions for future research on future material consumption, together with more practical improvement possibilities of the model.

2 Introduction to iron and steel production

2.1 General description of technologies

In this chapter, we give a brief introduction to the technologies applied in the iron and steel industry. Detailed historical data on production volumes, shares of various technologies in total steel production and total energy use of the iron and steel industry will be given in the following three chapters. For more detailed descriptions of the various technologies we refer to the Best Available Technique Reference Documents published by the European Commission (IPTS, 2001a,b, 2005) and other studies such as Daniels (2002) and de Beer (1998). The text below is to a large extent based on these sources. The production of steel products can be divided into five distinct steps (Figure 2-1):

- Treatment of raw materials
- Iron making
- Steel making
- Casting
- Rolling and finishing

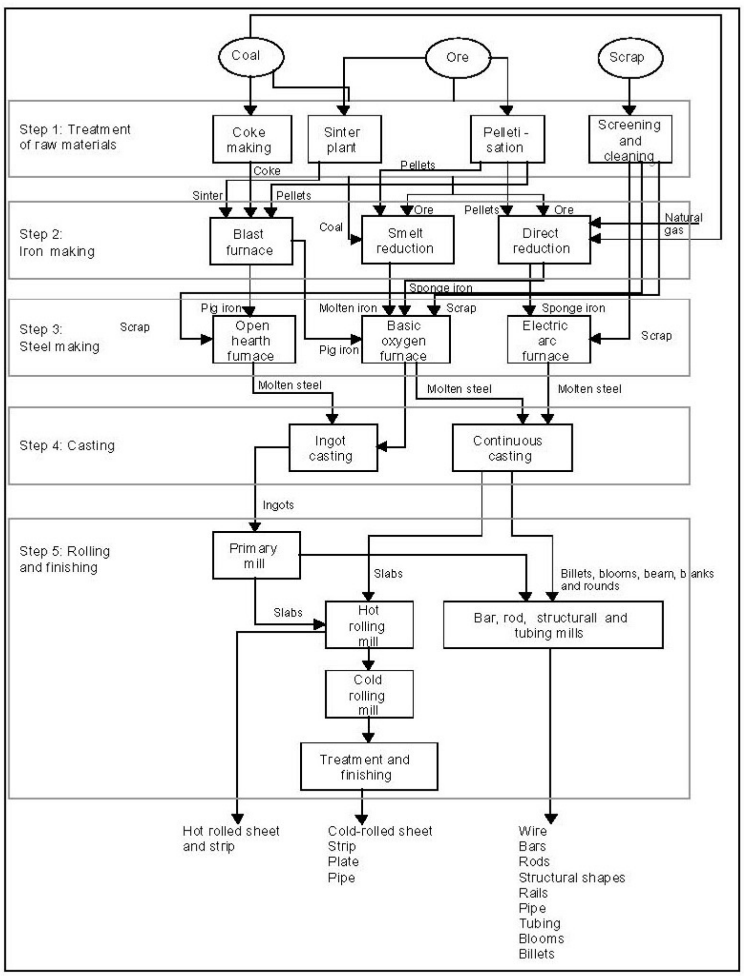

Figure 2-1 Processes for steel production (OECD and IEA, 2001).

Steel is produced from either primary iron (made from iron ore), secondary iron (scrap) or a mixture of both. In 2004, the production of crude steel exceeded 1 billion tonnes for the first time (IISI, 2005a). The worldwide share of secondary inputs into steel making was approximately 40% (including inputs into foundries, see Section 2.4), but large differences exist between countries and regions (see further in this report). Iron ore occurs in the natural environment as lump ore and fine ore. Lump ore is a suitable feed for various processes, but is more expensive than fine ore. Fine ores can often not directly be applied in iron production processes. For economic reasons, it is attractive to process fine ore into larger aggregates such as pellets and sinter rather than to use lump ore (Daniels, 2002). Also scrap needs some pre-processing (cleaning, quality checks etc.) before it can be used for steelmaking.

In iron making, iron oxides are reduced to iron. One method is to reduce iron ore with carbon above the melting point resulting in liquid pig iron (PI) containing between 4 and 6% of dissolved carbon. The gangue materials present in the ore separates from the liquid iron and floats on it (Daniels, 2002). In 2004, 720 Mt of pig ion was produced (IISI, 2005a). Almost all pig iron is produced with blast furnaces requiring coke for structural reasons. Cokes are produced from coking coal with coal tar and coke oven gas as side-products. Smelt reduction is an alternative pig iron production technology using coal instead of coke. Reduction in smelt reduction processes normally takes places in two separate reactors: the pre-reduction shaft and a smelting reduction vessel, but many different process layouts have been proposed (de Beer, 1998). Currently one smelt reduction process, the COREX/FINEX process is commercially applied in three plants worldwide (Wieder et al., 2004). The total yearly capacity is approximately 3 Mt / year. Another process close to commercial application is the HIsmelt process. A commercial scale plant (capacity of 800 kt/year) is currently being constructed in Australia, was expected to start up in late 2004 and to reach full production in the first half of 2006 (Rio Tinto, 2002). Iron ore can also be reduced below the melting point of the ore resulting in a solid product referred to as Direct Reduced Iron (DRI) or Hot Briquette Iron (HBI). At the reduction temperature, carbon does not dissolve in the iron and DRI/HBI therefore hardly contains any carbon. DRI/HBI retains the original shape of the ore and still contains the gangue material present in the ore (Daniels, 2002). The worldwide production of DRI/HBI in 2004 was 55 Mt. In approximately 90% of the DRI/HBI production, natural gas rather than coal is used as reductant (Midrex, 2004).

Steel is produced from primary and secondary iron sources in basic oxygen furnaces (BOF), electric arc furnaces (EAF) and the outdated open-hearth furnaces (OHF), which are still used in India and parts of Eastern Europe and the former Soviet Union. In the BOF process, which is always integrated with the production of pig iron, oxygen blowing converts the pig iron to steel by the oxidation of carbon, silicon and phosphorus present in pig iron. A variable amount of scrap is used as additional input for cooling purposes. In the OHF, the heat of a flame melts variable combinations of scrap and primary iron. In EAF steel production, melting of scrap and primary iron takes place in a bath at high temperatures achieved with the help of electric arcs. The worldwide division between the steelmaking processes in 2004 was 63% (BOF), 34% (EAF) and 3% (OHF) (IISI, 2005a).

The liquid steel produced by the steel production technologies used to be cast into large ingots but is now mainly continuously cast into semi-finished products such as slabs. During various rolling and finishing steps, the steel is then converted to finished steel products.

2.2 Overview of primary and secondary inputs into steel production

A summary of primary (PI and DRI) and secondary iron inputs into the three steel producing processes is presented in Table 2-1.

Table 2-1 Overview of iron sources in steel making technologies (Mishin, 2002)

Process	Share of scrap (%)	Share of PI (%)	Share of DRI (%)
BOF	3-25	76-97	-
EAF	0-100	0-40	0-100
OHF	30-95	0-70	-

The table shows that the flexibility of iron inputs into OHF and EAF is large. The EAF is often associated directly with secondary steel production, but increasingly, primary iron is charged to EAF. The EAF route is therefore by no means synonymous to secondary steel production anymore. This also becomes clear from the following quote:

'*As late as the 1980s, virtually all electric arc furnaces ran on a 100% scrap charge and almost no alternative iron (AI) was used. The term "alternative iron" refers to virgin charge materials, and includes direct reduced iron (DRI), hot briquetted iron (HBI), merchant pig iron (PI), and hot metal (HM). Today, the percentage of alternative iron fed to the EAF in North America is over 15%, and worldwide over 20 %. DRI alone now comprises about 8% of the charge mix in North America, 13% globally' (Kopfle et al., 2001).*

These estimates are confirmed in the global metallics balance for EAF in 2001 given by Cattell et al. (Table 2-2).

Table 2-2 Worldwide metallics balance for EAF in 2001 (Cattell et al., 2002)

	Mt	Percentage
EAF steel production	283	
EAF metallics consumption	310	100
- Merchant pig iron	22	7.1
- Alternative hot metal[1]	3.5	1.1
- DRI/HBI	41	13.2
- Scrap	244	78.6

[1]Liquid iron produced via smelt reduction processes

We will show in our overview of historical trends (Chapter 4) that this worldwide balance hides substantial regional differences in iron source for electric arc furnaces. In some regions, EAFs are almost exclusively charged with DRI, making the EAF route a *primary* rather than a *secondary* steel route for those regions. The choice for a certain steel production technology (EAF or BOF) and the choice of the iron sources used in the steel production technology (primary iron or scrap) is influenced by many things such as:

- The quality requirements for the various steel products.
- The availability of scrap of sufficient quality of produce certain steel qualities.
- The required investment (EAF requires less investment than integrated steel plant)

Below are some remarks from various sources on the rather complex subject of scrap availability in relation to required steel quality:

1. *The scrap availability is insufficient to meet the still growing demand for steel and the global recycling rate is near the maximum. In the future, the demand for steel is likely to grow at a slower rate, and may even stabilize in the long term. Then, the insufficient availability of good quality scrap, required for prime quality steel, will become the main constraint for attaining a much higher recycling rate (Daniels, 2002, pp. 14).*
2. *Recycled steel scrap is a very flexible raw material because steel scrap form any source can re-cycled to make around 80% of the total range of steel products produced (Eurofer, 1999, pp. 7)*

3. *The recent introduction of thin-strip casting enables the mini-mills to produce thin steel strip without the too expensive large-scale mills previously required. As a consequence, mini-mills in the US are entering the market for deep drawing steel, previously closed to them. Deep drawing steel is mainly applied in the automobile production (Daniels, 2002 pp. 46).*
4. *The proportion of EAF in flat vs. long products is expected to increase sharply from 8-92% to 20-80%* (note authors: in the period 1998-2010), *which means an increase of flat EAF products from 20 to 66 Mt/y and a relative stagnation of long products at 264 from 230 Mt/y (Birat, 2000, pp. 1352).*
5. *The first factor is that the scrap market and the way prices are established is mainly fixed by the growing demand of EAFs and mini mills and the growing supply of obsolete scrap.... The second factor is that in the past the market for scrap, mainly EAFs in mini mills, was different from the market for iron ore or the primary metals from iron ore, practically only pig iron.... Iron ore and pig iron were used in integrated iron and steel plants; mini mills were accounting for a growing proportion of long products while the integrated plants were concentrating on flat products... Now, the mini mills are 'invading' all types of product sectors, especially in the US and the competition is growing between collected scrap and the primary metals produced from iron ores, i.e. pig iron and DRI/HBI including iron carbide (UN, 1999, pp. 73).*
6. *The areas where recycled scrap is processed tend to be those areas where steelmaking is not growing, and the areas where steelmaking is growing tend to be the areas that are not self-sufficient in scrap generation – so we have a physical problem. Steve Mackrell as quoted by the Bureau of International Recycling (Bureau of International Recycling, 2004).*

From these quotes, we draw the following conclusions:

1. The majority of steel products can in principle be produced out of secondary resources (quote 2) and steel produced from secondary resources in electric arc furnaces invade also the market for flat steel products (quote 3,4, and 5).
2. The availability of scrap is an important parameter determining the choice for a certain steel production route (quote 1,5, and 6).

2.3 Energy use

Specific (i.e. per tonne of product) final and primary energy consumption figures can be found in many different literature sources. The system boundaries applied and assumptions made are, however, not always 100% clear and consistent, so a sound comparison of data is not always straightforward. Allocation of energy use to the various individual process units within the steel making process is not easy, because of the energy integration between various parts of the process. In Table 2-3, we present an overview of typical primary energy intensity ranges for the various individual processes (Price et al., 2002).

Combination of certain process steps yields specific energy use estimates for the production of steel products. Typical ranges for hot rolled steel products are 15.8 – 25.3 GJ / tonne for products produced via the primary route via pig iron / basic oxygen furnace / continuous casting / hot rolling and 17.3 – 29.3 GJ / tonne via the primary route via direct reduced iron / electric arc furnace / continuous casting / hot rolling. Secondary production requires 6.4 – 12.2 GJ / tonne via the electric arc furnace / continuous casting / hot rolling route. Cold rolled products require 1.6 – 2.8 GJ / tonne in addition. Thin slab casting, combining the casting and hot rolling step and can reduce the specific energy use by 1-3 GJ / tonne (IEA, 2006).

Table 2-3 Ranges of primary energy intensities of key iron- and steelmaking processes (Price et al., 2002).

Process	**Ranges of Primary Energy Intensity GJ / tonne of steel**
Ironmaking[1] – Pig iron (PI)	12.7 – 18.6
Ironmaking[1] – Smelt reduction (SR)	13.0 – 18.0
Ironmaking[1,2] – Direct reduced iron (DRI)	10.9 – 16.9
Steelmaking – Open heart furnace (OHF)	3.9 – 5.0
Steelmaking – Basic oxygen furnace (BOF)	0.7 – 1.0
Steelmaking – DRI + electric arc furnace (EAF)[2]	4.0 – 6.7
Steelmaking – Scrap + electric arc furnace (EAF)	4.0 – 6.5
Casting – Ingot casting	1.2 – 3.2
Casting – Continuous casting	0.1 – 0.3
Casting – Thin slab casting	0.6 – 0.9
Rolling – Hot rolling	2.3 – 5.4
Rolling – Cold rolling	1.6 – 2.8

[1] Iron making includes energy used for ore preparation and coke making.
[2] Iron making – DRI and Steelmaking – DRI + EAF assume 80% DRI and 20% scrap.

The overview shows that by the most energy intensive step is the production of primary iron from iron ore. This is not surprising since the minimal theoretical energy requirement of converting Fe_2O_3 to pure Fe is already equal to 6.6 GJ / tonne Fe (de Beer, 1998). The theoretical minimal energy requirement for secondary steel making is close to 0 GJ / tonne. It should be noted, however, that steel is always shaped in the form of liquid steel. Minimal energy requirements for melting iron or steel are between 1 and 1.4 GJ / tonne, depending on e.g. the carbon content of the steel (de Beer, 1998). In principal, this heat can be recovered when the iron or steel cools down to environmental temperature. In electric arc furnaces, the energy for melting is supplied in the form of electricity. In modern electric arc furnaces, the electricity input (~1.5 GJ / tonne) exceeds the energy required for melting approximately by 10% (de Beer, 1998). In integrated steel mills, the pig iron produced is already in liquid form. In the production of steel from pig iron in the basic oxygen furnace, even more energy is released as a result of the oxidation of the carbon in the pig iron.

2.4 Iron and steel foundries

Certain iron and steel products are produced in the foundry industry. *'Foundries melt ferrous metals and alloys and reshape them into products at or near their finished shape though the pouring and solidification of the molten metal or alloy into a mould. The foundry industry is a differentiated and diverse industry... Since castings in general are semi-finished products, foundries are located close to their customers'* (IPTS, 2005, pp. iv). Since we develop in our study (see Chapter 4 for a detailed explanation) a material flow model for the iron and steel industry, the iron and steel castings produced by the foundry industry cannot be neglected. In the US and Europe, the production of iron castings is nowadays less than 10% of the steel consumption as we will show in the next chapter, but for other regions, castings might have a larger market share.

3 Demand for steel

3.1 Conceptual modelling approaches

3.1.1 Dematerialization and intensity of use

In modelling future demand for steel (or any other material) over longer periods of time (more than 10 years), it is most common to couple the demand of steel to driving variables related to the socio-economic development of the country or region under consideration.

The ratio between the demand for materials and these socio-economic variables can be referred to as the intensity of use (IU). In the last decades, IU patterns for various materials and especially metals have been studied in quite some detail. Cleveland and Ruth (1999) give an overview of these studies. At an economy-wide level of aggregation, the $IU_{\$}$ can be defined as the material consumption per unit of Gross Domestic Product (GDP). The trend in this aggregated $IU_{\$}$ indicator is the superposition of two generic underlying trends (Cleveland and Ruth, 1999):

1. Trends in the product composition of income (i.e. the economic structure)
2. Trends in the material composition of products (the materials used to produce certain goods and services)

The two are interlinked by the following accounting identity that describes the total consumption of material *x* in a national economy, consisting of *n* sectors *j* with output *Y*:

$$IU_{\$,x,t} = \frac{x_t}{GDP_t} = \sum_{j=1}^{n} \left(\frac{Y_{j,t}}{GDP_t} \right) \left(\frac{X_t}{Y_{j,t}} \right)$$

Equation 3-1

The consumption per capita (IU_{cap})[3] can be derived directly from Equation 3-1 by multiplication with the per capita income (GDP_{cap}):

$$IU_{cap,x,t} = IU_{\$,x,t} * GDP_{cap,t}$$

Equation 3-2

Some studies (e.g. Malenbaum, 1978, Williams and Larson, 1987 and Tilton, 1990) have empirically shown that the aggregate $IU_{\$}$ curve (x/GDP) for a number of materials has an inverse-U or bell shape when plotted as function of per capita income. The relationship for steel will be shown below in Section 3.3.1 (Figure 3-4) for the various TIMER regions. Two arguments are used in the explanation of this observed behaviour:

The first argument is that the production composition of income (economic structure) of a country varies in different stages of a country's development. In early stages of development, economies largely rely on agriculture with low material requirements. When a country develops, the demand for basic infrastructure (buildings, transportation equipment etc.) increases and the share of material-intensive sectors in the economy grows. As development further continues, consumer preferences shift to less material-intensive products, causing the

[3] In the formula, we refer to the consumption per capita with IU_{cap}.

intensity of use to go down, resulting in the observed inverse U shape of the $IU_\$$ as function of per capita income, especially for products that are mainly used in the production of infrastructure such as metals and cement.

The second argument used in the explanation of the inverse U shape is more related to the material composition of product and explains the observed inverse-U shape by suggesting that the material demand experience phases in which old, lower quality materials linked to mature industries undergo replacement by higher quality or technologically more advanced materials (Labys, 2004). For individual materials, this lead to phases of expanding use (the new material substitutes existing materials), stabilising use (demand for the main end-use of the material saturates) and declining use (the material is increasingly being substituted by other materials). A third additional argument, often used to explain the declining intensity of use in developed countries is the continuously increased efficiency of material use, leading to a more efficient use of certain materials over time.

It is important to note that the main independent variable used to explain the observed $IU_\$$ curve differs between the three arguments mentioned. In the first argument, *income* is the independent variable and the argument in principle holds for all developing countries irrespective of the time in which development takes place. In the second and third argument, *time* is the independent variable. As a result, the $IU_\$$ curve for countries that develop in various periods of time can, according to these two arguments be expected to differ, which should be considered when developing a long term worldwide steel demand model. Bernardini and Galli (1993) include both the time and income dependency in the '*two basic postulates that together constitute the theory of dematerialization'*:

1. *'The intensity of use ($IU_\$$) follows the same pattern for all economies, at first increasing with per capita GDP, reaching a maximum at about the same per capita GDP, and eventually declining;*
2. *'The maximum intensity of use ($IU_\$$) declines the later in time it is attained by a given economy.'*

In Figure 3-1, we give a schematic representation of possible idealised curves resulting from these postulates in four different years 2003, 2020, 2050 and 2100. As can be seen in the right figure, the $IU_\$$ first increases, reaches a maximum and declines afterwards (postulate 1). In 2020, the curve has a lower maximum compared to 2003 and in 2050 and 2100, the maximum is even lower (postulate 2). The per capita saturation behaviour shown in the left figure is not a direct result of the two postulates. One could also draw declining $IU_\$$ curves with an increasing or decreasing per capita consumption at high per capita incomes.

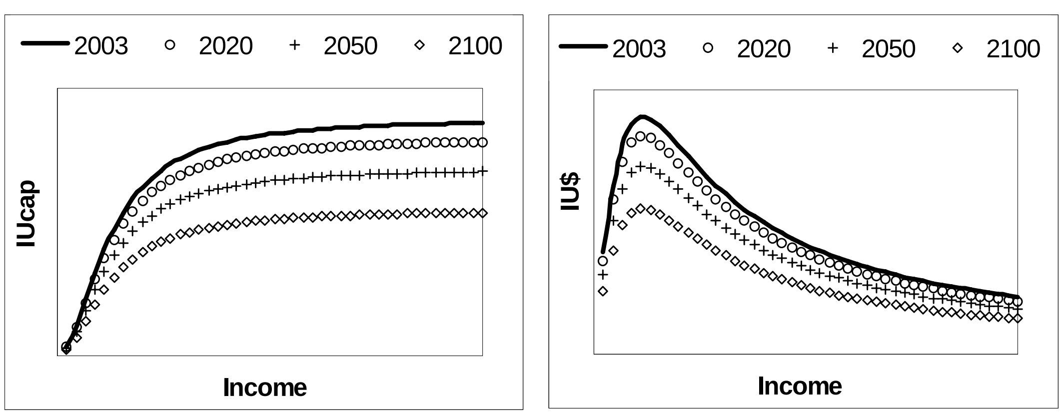

Figure 3-1 Schematic picture of intensity of use and per capita consumption

It is obvious that technological progress not only influences the maximum level of the intensity of use, but also the income level at which a country reaches this maximum. Substitution between types of materials used for certain applications has an effect on the structural changes projected by the intensity of use curve. The curves given in Figure 3-1 should therefore be regarded as idealised curves resulting from the two postulates given above (with the exception of the per capita saturation behaviour as explained above) and certainly not as curves in which all elements in the 'intensity of use' debate are taken into account in a decisive way.

3.1.2 Overview of existing models with steel demand projections

In Appendix 2, we give an overview of existing studies / models projecting steel demand in the short and longer term. The models differ in the way they incorporate the dependency of the IU curves on income, time and additional parameters. They all make use, in one form or another, of the accounting identity presented in Equation 3-1.

Van Vuuren et al. (1999) and Hidalgo et al. (2005) project steel demand until 2100 and 2030 respectively, using an aggregate $IU_\$$ curve that follows an inverted U or bell-shape curve as function of per capita income. Van Vuuren et al. (1999) use an equation that results in a saturated constant steel demand per capita at high-income levels:

$$IU_{\$,t} = \frac{\alpha}{GDP_{cap,ppp,t} + \beta * GDP^{\gamma}_{cap,ppp,t}}$$

Equation 3-3

In this formula, the parameter α is the per capita saturation level and the parameter β and γ determine the form of the $IU_\$$ curve. In the study, an additional factor F is used that can be used to scale down demand from historic trends to account for technological progress. In the final demand equation, an additional factor P is added that describes the effect of prices on demand using a simple elasticity approach.

In the study by Hidalgo et al. (2003), the following equation is used to project steel demand

$$IU_{\$,t} = e^{\left(\alpha + LN(IU_{\$,t-1}) + \beta * \left(\frac{1}{GDP_{cap,ppp,t}} - \frac{1}{GDP_{cap,ppp,t-1}}\right) + \gamma * (GDP_{cap,ppp,t-1} - GDP_{cap,ppp,t})\right)}$$

Equation 3-4

The function yields continuously declining per capita consumption levels when time proceeds as a result of the parameter α. This parameter might therefore be used to simulate technological progress over time but unfortunately little background is given on the selection and calibration of the parameters in the model. Comparable to the model by Van Vuuren et al. (1999), steel prices in combination with steel price elasticities are included to model the effect of varying steel prices on steel demand. In Chapter 7, we compare the projections generated with our modelling approach with the results obtained by the two models discussed above.

Other mathematical expressions that are used to model the inverted U-shaped form of the $IU_\$$ curve are the expression used in the VLEEM model (VLEEM, 2005, discussed in more detail in the next section) and the expression used in the TIMER model (de Vries et al., 2001):

$$IU_{\$,t} = IU_{\$,0} + \frac{1}{\alpha + \beta * GDP_{cap,ppp,t} + \gamma * GDP^{\delta}_{cap,ppp,t}}$$

Equation 3-5

At high-income levels, this equation approaches a saturation level equal to 1/α. The three other parameters determine the dynamic behaviour of the expression and can be used to shape the form of the resulting $IU_{\$}$ curve. They can for example be used to vary the income level at which the $IU_{\$}$ reaches its maximum and the maximum $IU_{\$}$ at this income level (de Vries et al, 2001). The medium-term steel demand projections by Das and Kandpal (1998) and Michaelis and Jackson (2002) also use the Intensity of Use approach based on regression analysis of historical data (Das and Kandpal) or by simple extrapolation of the historical curve (Michaelis and Jackson).

Roberts (1990) studied in more detail the two underlying trends (product composition of income and material composition of products) for three major steel consuming sectors in the US for the period 1963-1983. He used his findings for a long-term steel consumption projection for the US until 2010. Crompton (2000), who projects steel consumption in Japan for 1997-2005 based on data for 1950-1997 follows a similar approach. Both studies show a declining material composition of product over time, measured in kg per unit of economic output for the various steel consuming sectors, confirming material efficiency improvements in the sectors studied over time. Studies by Hwang and Tilton (1990) and Lohani and Tilton (1993) who have further studied the time dependency of the IU curves for a number of developing countries also confirm this.

Vector auto regression analyses using historical correlations between a number of selected variables (such as GDP and steel prices) to extrapolate values of the variables in the future are used by Crompton (1999) and Chen et al. (1991) to project steel consumption in the medium term (0 to 10 years) for South-East Asia and China. Gielen and Moriguchi (2002) use income elasticities for eight steel demand categories to project Japanese steel demand until 2030, complemented with price elasticities to model the influence of steel prices on steel demand. A similar approach is taken by Mannaerts (2000), who models the influence of income, own prices, energy prices and the investment share of GDP on steel and other material demand until 2020 using elasticities for each of the factors mentioned. Time dependency of steel demand is included by using a declining income elasticity over time.

3.2 General description of modelling approach

Given the focus of this study on developing a long-term worldwide projection for the steel industry that can also be used in the TIMER model, we decided to choose an approach for projecting steel demand that only uses the main driving forces used in the TIMER model: population and per capita income. We decided to stay close to the approaches chosen by van Vuuren et al. (1999), Hidalgo et al. (2005) and in the VLEEM model (2005) in projecting steel demand. This means that we use an $IU_{\$}$ curve that follows an inverted U or bell-shape curve as function of per capita income and has per capita saturation at high-income levels. To be able to include also the effect of material efficiency improvements over time that lowers demand when time proceeds, we include a time-dependent material efficiency factor. We tested various mathematical expressions (including the expressions used in the TIMER model and by van Vuuren et al.) and finally decided to use mathematical expression used previously also in the VLEEM model (2005), because it was the most simple equation:

$$IU_{cap,t} = \alpha * e^{(\beta / GDP_{cap,ppp,t})}$$

Equation 3-6

With:

$IU_{cap,t}$: intensity of use (t / capita)

$GDP_{cap,ppp,t}$: GDP per capita (1995 ppp $ / capita)
α: shape parameter
β: shape parameter

The expression also has the advantage that both shape parameters α and β have a direct physical meaning, as we will show below[4]. From Equation 3-2 it becomes clear that the corresponding $IU_{\$,t}$ equals:

$$IU_{\$,t} = (\alpha * e^{(\beta / GDP_{cap,ppp,t})}) / GDP_{cap,ppp,t}$$

Equation 3-7

Parameter α in the equation is the long-term saturation level of the IU_{cap}, because the exponential term approaches 0 at high-income levels.

The income elasticity of the IU_{cap} equals by definition:

$$Income\ elasticity\ IU_{cap,t} = \frac{d\ IU_{cap,t}}{d\ GDP_{cap,ppp,t}} * \frac{GDP_{cap,ppp,t}}{IU_{cap,t}}$$

Equation 3-8

For the mathematical equation used in our model (Equation 3-6), the income elasticity equals:

$$Income\ elasticity\ IU_{cap,t} = \frac{-\beta}{GDP_{cap,ppp,t}}$$

Equation 3-9

From Equation 3-9 it becomes clear that the parameter –β equals the per capita income level where the income elasticity is 1. Below this level, the income elasticity is higher than 1 (relative growth in IU_{cap} exceeds relative growth in income) and at income levels above –β, the income elasticity is lower than 1 (relative growth in IU_{cap} is lower than relative growth in income).

Following the chain rule for derivatives of the product of two differentiable functions, it can be proven that the derivative of any $IU_\$$ function (Equation 3-2) is equal to:

$$\frac{d\ IU_{\$,t}}{d\ GDP_{cap,ppp,t}} = \frac{-IU_{cap}}{(GDP_{cap,ppp,t})^2} + \frac{1}{GDP_{cap,ppp,t}} * \frac{d\ IU_{cap,t}}{d\ GDP_{cap,ppp,t}}$$

Equation 3-10

[4] This does not mean that the shape parameters in the other mathematical expression do not have a physical meaning. De Vries et al. (2001) show for example that the maximum in the intensity of use curve used in the TIMER model and the income level at which this maximum occurs can also be expressed as function of the four shape parameters. However, in the mathematical expression we use, the physical meaning is a direct one (per capita saturation level and the maximum in the IU curve).

For an $IU_\$$ curve with an inverted U shape (see Figure 3-1), the derivative of the $IU_\$$ at the maximum value of the $IU_\$$ is 0. In this point (derivative = 0), Equation 3-10 can be rewritten as:

$$\frac{IU_{cap}}{GDP_{cap,ppp,t}} = \frac{d\ IU_{cap,t}}{d\ GDP_{cap,ppp,t}}$$

Equation 3-11

By definition, this point also corresponds to a point where the income elasticity of the IU_{cap} is equal to 1 (rewrite Equation 3-8 under that condition that the income elasticity is 1). We just showed, that for the curve used in our model, this point corresponds to an income level of –β. This can also be proven directly for the equations used in our model by taking the derivative of the $IU_\$$ curve (Equation 3-7):

$$\frac{d\ IU_{\$,t}}{d\ GDP_{cap,ppp,t}} = \frac{-\alpha * e^{(\beta / gdp_{cap,ppp,t})}}{(GDP_{cap,ppp,t})^2} + \frac{-\alpha * \beta * e^{(\beta / gdp_{cap,ppp,t})}}{(GDP_{cap,ppp,t})^3}$$

Equation 3-12

At income levels of –β, this derivative is equal to 0.

From the above, we derive the following characteristics for the curve used in our model.

- The variable α in our equation corresponds to the saturation level per capita at high income levels
- The parameter –β corresponds to the per capita income level where the $IU_\$$ reaches its maximum. By definition this per capita income level also corresponds to the point where the income elasticity of the IU_{cap} is 1. The income elasticity is below 1 at income levels above –β and above 1 at income levels below –β.

To include the time-dependency of the IU curves, we extend our basic equation with a factor that can shift the curve up and down as a function of time:

$$IU_{cap,t} = \alpha * e^{(\beta / GDP_{cap,ppp,t})} * time\ \ factor(t)$$

Equation 3-13

The time factor (t) can for example be used to model a certain yearly material efficiency improvement that shifts the IU_{cap} curve down as time proceeds:

$$time\ \ factor = (1 - material\ efficiency\ \ factor)\text{^}(t - 2003)$$

Equation 3-14

It would of course be possible to use other formulas to calculate the time dependency of the intensity of use curve. With the combination of Equation 3-13 and Equation 3-14, we are able to simulate intensity of use curves of the form shown in Figure 3-1. In Section 3.4, we derive the model variables based on historical trends.

3.3 Overview of past trends and data used for estimating model parameters

3.3.1 Apparent crude steel consumption

Apparent consumption data for crude steel are available from the International Iron and Steel Institute (IISI, various years). An overview of worldwide crude steel production for 1900-2003 is given in Figure 3-2. A split into TIMER regions for the period 1970-2003 is given in Figure 3-3.

Apparent crude steel consumption is calculated in the IISI statistical yearbooks[5] as the production of crude steel + import - export of semi-finished and finished steel products in crude steel equivalents. The import and export of finished steel products are converted into crude steel equivalents by multiplication with the following factor:

$$(1.3) / (1 + 0.175\, c)$$

Equation 3-15

Where c is the domestic proportion of crude steel that is continuously cast. This formula reflects the fact that steel losses (in the form of scrap) in the production of semi-finished and finished steel products are much lower in the case of continuous casting compared to ingot casting. In case of 100% ingot casting, imports and exports of finished steel products are multiplied with a factor 1.3, in case of 100% continuous casting, imports and exports of finished steel products are multiplied with a factor 1.11. For countries where imports predominate, the average continuous-casting of the major exporters is used.

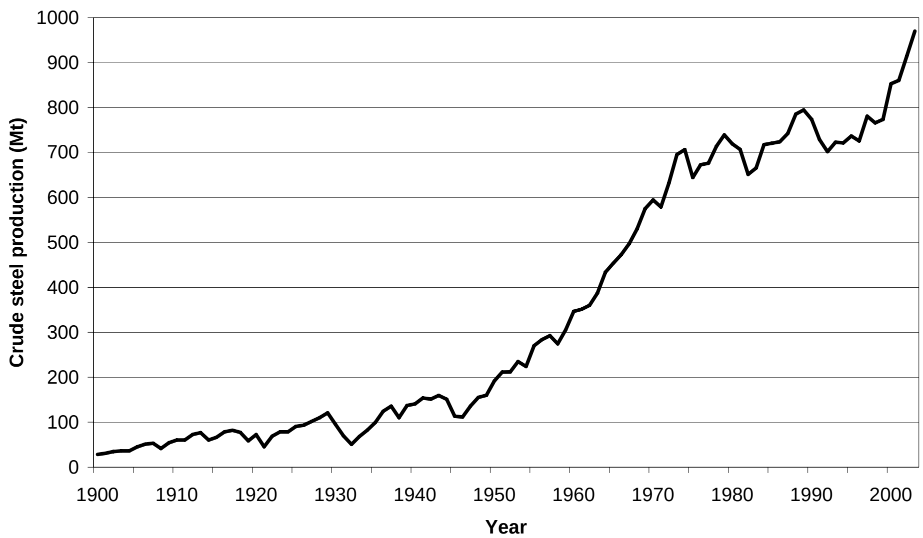

Figure 3-2 Apparent worldwide crude steel production, 1900-2003 (IISI, Various years)

[5] For the data used in the study, we used the yearbooks of 1980, 1990, 2000, 2003 and 2004. The method given here is used in the yearbooks of 1990, 2000 and 2003. In the yearbook of 2004, no reference is made to any method to calculate crude steel equivalents from finished steel imports and exports, but most likely the same method is used. In the yearbook of 1980, a different method is used with different factors for various types of semi-finished and finished steel products.

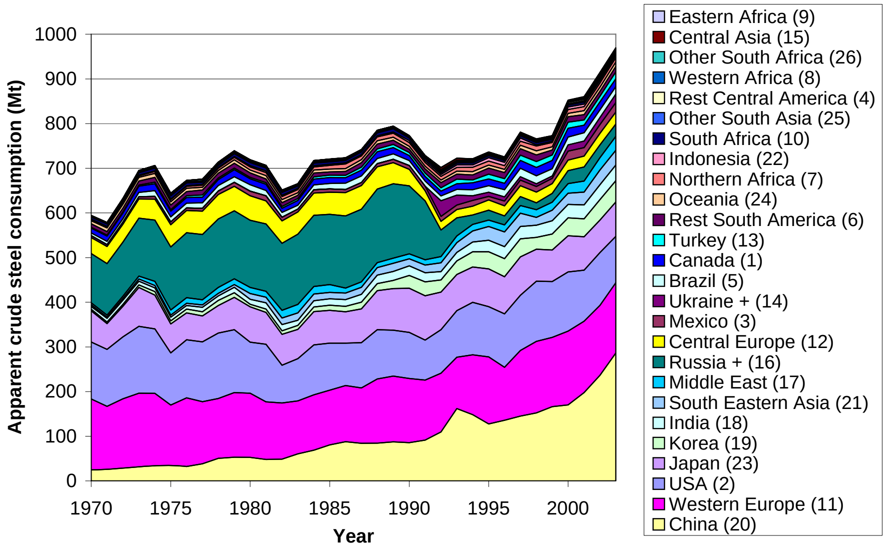

Figure 3-3 **Apparent crude steel consumption from 1970-2003 in the 26 TIMER regions in the order of decreasing crude steel consumption in 2003 (IISI, Various years). Before 1992, Baltic states (part of Region 12), Ukraine + (Region 14) and Central Asia (Region 15) within Russia + (Region 16).**

Figure 3-3 visualises the increase in steel consumption in China in recent years, the decrease in consumption in the former USSR regions and Central Europe after the collapse of the centrally planned economies at the beginning of the nineties and the relatively stable steel consumption in Western Europe, North America, Japan and Oceania. Apparent consumption data per unit of GDP ($IU_{\$}$) or per capita ($IU_{cap}$) are often used as indicators to project steel demand in the future (Section 3.1.2). The $IU_{\$}$ and IU_{cap} for steel in the 26 TIMER regions are given in Figure 3-4 and Figure 3-5 as a function of GDP per capita for the period 1970-2003. Data sources are given in Appendix 3. The estimates are based on purchasing power parities (expressed in constant 1995 ppp \$).

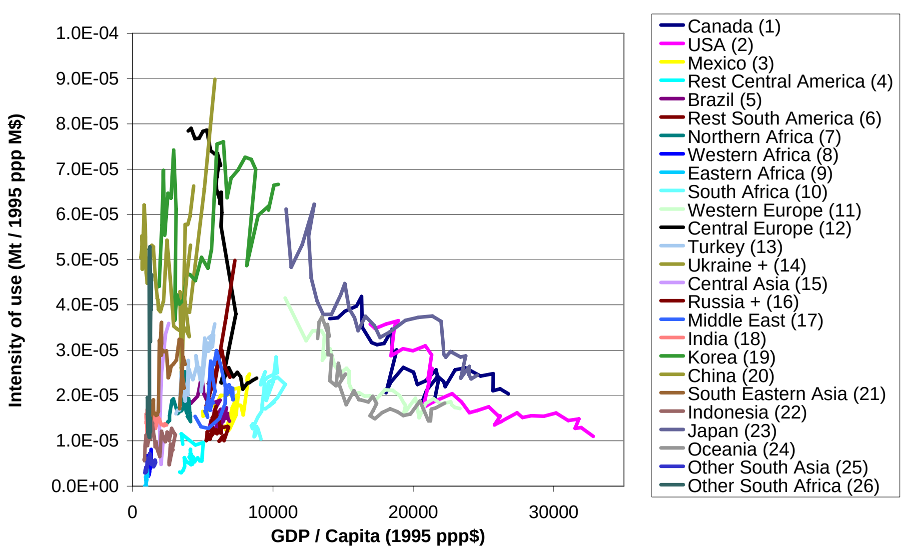

Figure 3-4 **Apparent crude steel consumption per unit of GDP (1995 ppp \$) for the 26 TIMER regions from 1970-2003. Regions from the former USSR (Region 14, 15 and 16) are only shown from 1992 onwards.**

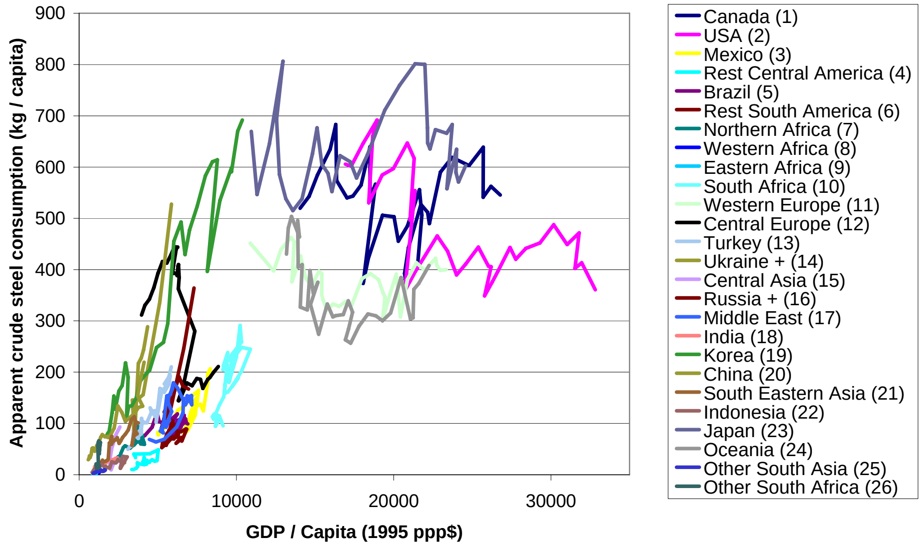

Figure 3-5 **Apparent crude steel consumption per capita for the 26 TIMER regions from 1970-2003. Regions from the former USSR (Region 14, 15 and 16) are only shown from 1992 onwards.**

Visual inspection of Figure 3-4 reveals that the developed regions (Canada, USA, Western Europe, Japan and Oceania) show a declining $IU_\$$ and stabilising IU_{cap} levels. Part of the decline in demand between 1970 and 2003 can be explained by the introduction of the continuous casting that replaced ingot casting in this period. The worldwide continuous casting ratio went up from 8% in 1972 to 90% in 2003 (IISI, Various years). Using Equation 3-15, this implies that in 2003, 970 Mt of crude steel was required to produce 863 Mt of finished steel (ratio of 1.12 tonne / tonne), whereas in 1972, 695 Mt of crude steel was required for 544 Mt of finished steel (ratio of 1.28 tonne/tonne). In other words, 12% less crude steel was required in 2003 to produce the same amount of finished steel products as in 1972. This is further visualised in Figure 3-6 where the trend in crude and finished steel consumption for the period 1972-2003 is shown.

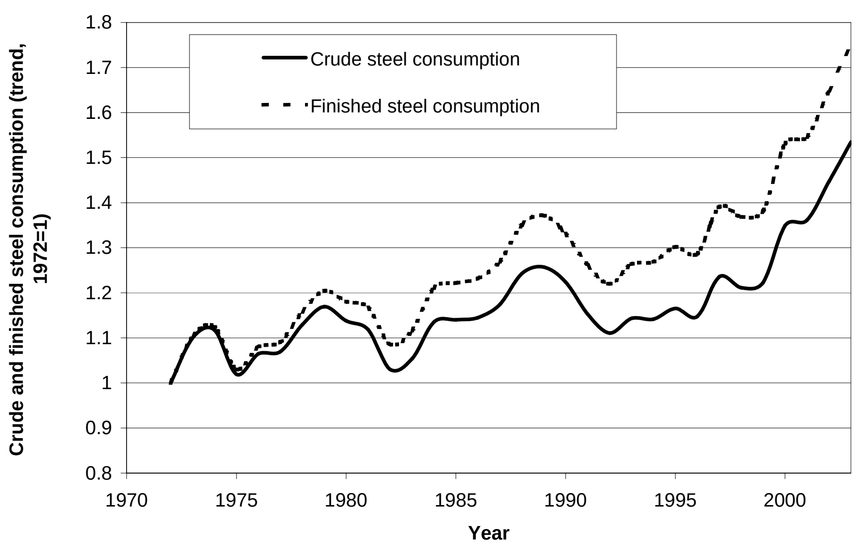

Figure 3-6 **Crude steel and finished steel consumption trends 1972-2003. Finished steel consumption derived from crude steel consumption (Figure 3-2) using Equation 3-15.**

It is important to realize that the apparent consumption figures shown so far do not include indirect trade of steel that is contained in steel-containing products such as cars, but only trade in semi-finished and finished steel products. The figures are therefore only an approximation of the actual final consumption of steel containing products. The International Iron and Steel Institute (IISI) in the past studied these indirect trade flows by studying the trade in some of the major steel containing products such as cars for some major trading countries. The last year for which data is available is 1993. We show the final consumption of steel in products (including the indirect trade) as a percentage of the direct final consumption of finished steel products (only taking into account trade in semi-finished and finished steel products) in Table 3-1. Most of the countries are net exporters of steel containing end products, while Switzerland and the US are net importers. Table 3-1 shows that apparent consumption of crude steel as shown in Figure 3-3 - Figure 3-5 can differ significantly from the consumption of steel, taking into account trade in steel-containing products (up to 30% for the countries included in Table 3-1). This effect can (partly) explain the relatively high apparent consumption figures for Japan (region 23) and Korea (region 19) compared to other regions (compare Figure 3-5) and gives some idea about the uncertainties associated with the use of apparent crude steel consumption figures as approximation of the actual final consumption of steel in products in a region.

Table 3-1 Effect of indirect trade in 1993 for selected countries (IISI, 1996)

Country	**Final consumption as percentage of direct consumption (%)**
EC-8	87.6
Austria	98.9
Finland	83.1
Sweden	81.7
Switzerland	115.3
Japan	77.2
Korea	69.6
Taiwan	89.4
US	106.1
Total (for the countries included)	89.3

3.3.2 Production and consumption of iron castings from foundries

Foundries are important consumers of scrap and can therefore not be neglected in the material flow analysis used to project the amount of secondary steel (Chapter 4). In the model, we incorporate iron and steel foundries in a rather simple way. We neglect trade in foundry products and assume the production and consumption of iron foundry products to be a certain percentage of the crude steel consumption. In Table 3-2, we present an overview of iron casting production figures from literature. For developed regions production of iron castings as percentage of crude steel consumption is less than 10%. For less developed regions (e.g. India), the percentage is higher. In the past, the percentage has also been much higher in developed regions. In the US in 1938, the total input of pig iron and scrap into iron foundries in 1938 was 6.7 Mt (2.6 Mt pig iron, the rest scrap; USGS, 1939a,b) on a total crude steel consumption of 25.7 Mt. Using a specific input of 1.5 tonne per tonne of cast product (based on WSD, 2005), this corresponds to a production 4.5 Mt of iron castings, 17% of crude steel consumption. In Figure 3-7, we show historical data on crude steel consumption and iron castings production for the US for the period 1938-2003 based on data from World Steel Dynamics (WSD, 2005) for 1975-2003 and data from the US Geological Survey (USGS, various years) for 1935-1975.

Table 3-2 Estimates for current production of iron castings, crude steel production and ratio between the two

Country	Year	Crude steel consumption Mt[1]	Production of iron castings Mt	Iron castings as % of crude steel consumption
USA[2]	2003	103.9	8.2	8
Europe[3]	2002	170.5	11.4	7
UK[4]	2001	14.2	1.0	7
India[5]	2003	35.0	7.5	21
China[6]	1993	133.0	9.9	7
Japan[7]	2003	76.4	4.5	6
World[8]	1997	780.9	39 - 47	5-6

[1] Crude steel consumption figures based on IISI (Various years)
[2] Production of iron castings from US Geological Survey (USGS, 2004) including also steel castings.
[3] Production of iron castings from IPTS (2005) including also steel castings.
[4] Production of iron castings from Dahlstrom et al. (2004).
[5] The total capacity of foundries is 7.5 Mt according to the institute of Indian foundry men (2005). Probably also includes non-ferrous castings.
[6] Production of iron castings from China Foundry Association (2005).
[7] Production of iron castings from International Iron and Steel Institute (2005b).
[8] Total input of primary iron 29 Mt and total scrap input of 30-40 Mt (UN, 1999) results in foundry iron production of 39-47 Mt, assuming a specific input of 1.5 tonne / tonne (based on WSD, 2005). Authors admit that estimates are very uncertain. Based on the data for other countries, it can be concluded that the world estimate given here is too low.

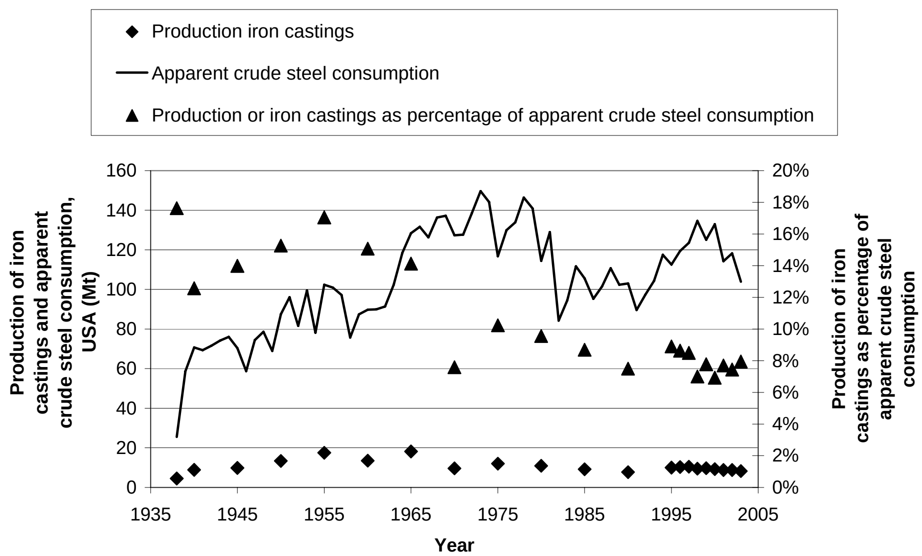

Figure 3-7 Apparent crude steel consumption and production or iron castings in the US and ratio between them in the US, 1935-2003

3.4 Detailed model description and exogenous model parameters

3.4.1 Apparent crude steel consumption

We developed a material flow model that already starts in 1900 (see Chapter 4 for more details). For 1900-1970, we use historical crude steel production data and assume that crude steel production equals apparent crude steel consumption (Appendix 3). From 1970-2003, we use historical apparent crude steel consumption data from the IISI statistical yearbooks (IISI, various years). We used the data for 1970-2003 shown in Figure 3-5 to fit Equation 3-13 and use Equation 3-14 as the time factor:

$$IU_{cap,t} = \alpha * e^{(\beta / GDP_{cap,ppp,t})} * (1 - material\ efficiency\ \ factor)\wedge(t - 2003)$$

Equation 3-16

In the period 1970 – 2003, already a substantial material efficiency improvement has taken place as a result of the introduction of continuous casting that replaced ingot casting. Shifting from ingot casting to continuous casting reduces the amount of crude steel required to produce an equal amount of finished steel by 15% (Equation 3-15). The amount of finished steel required for producing an amount of final consumer product also declined between 1970 and 2003 (Section 4.4.5). If we assume these effects to have taking place gradually from 1970 – 2003, this is equivalent to approximately 0.7% material efficiency improvement per year[6]. On top of the material efficiency improvements resulting from the introduction of continuous casting and from improvements in the conversion from finished steel to final consumer products, probably also additional material efficiency improvements have taken place in the sense that less steel is required to produce the same amount of final consumer products (e.g. the amount of steel required for a car). Using various assumptions for the material efficiency factor, we fitted the following curve using unconstrained non-linear regression in SPSS software (SPSS, 2005). The results are given in Table 3-3.

Table 3-3 Estimated parameters using various assumptions on the material efficiency factor

Material efficiency factor	α	β	R^2
0	735	-8806	0.734
0.0020	718	-8873	0.740
0.0040	701	-8944	0.744
0.0060	685	-9019	0.749
0.0080	667	-9097	0.751
0.0100	650	-9179	0.753
0.0120	633	-9265	0.753
0.0117[1]	**635**	**-9254**	**0.753**

[1] This value is calculated when the material efficiency factor is included as parameter in the regression

The results of the regression imply that a maximum intensity of use is obtained at a per capita income of around 9000 1995 ppp $ and that the per capita consumption saturates using 2003 material efficiency levels at 735 kg/capita (no material efficiency improvements assumed in the period 1970-2003) and at 633 kg/capita (material efficiency improvement of 1.2% per year assumed in the period 1970-2003). As shown before, material efficiency improvements have been at least 0.7 % per year as a result of improvements within the iron and steel and steel converting industry. This is confirmed by a regression analysis where we calculate the material efficiency factors as part of the regression. In that analysis (last row in the Table), an efficiency improvement of 1.17% per year in the period 1970-2003 is found. This implies that on top of the improvements resulting from the introduction of continuous casting and improvements in the conversion from finished steel to final products (0.7%), material efficiency improvements have been approximately 0.5% per year in the period 1970-2003. We show the regression results (material efficiency improvement of 1.17% per year in the period 1970-2003) as in Figure 3-8. As a result of the material efficiency factor, which is included in our approach (Equation 3-13 and Equation 3-14), the per capita consumption at

[6] To produce one tonne of final consumer product with ingot casting and with a prompt scrap ratio of 0.2 (Section 4.4.5), i.e. the situation in 1970, 1.63 tonne of crude steel is required. To produce the same amount via continuous casting and with a prompt scrap ratio of 0.13 requires only 1.28 tonne, 21% less. This is equivalent to yearly improvement of approximately 0.7% per year.

certain income levels is time-dependant. A country reaching a per capita income of 30,000 1995 ppp $ in 1970 consumed (according to our fitted curve) 700 kg of crude steel per capita, whereas a country reaching this income level in 2003 consumes only 480 kg of crude steel. For the period 2003-2100, we assume the further improvements in the conversion from crude to finished steel and in the conversion of finished steel to final products (Section 4.4.4 and Section 4.4.5) equivalent to approximately 0.15% per year[7]. If we add a yearly 0.5% material efficiency improvement in the use of final products to this total, we end up with a material efficiency improvement of 0.65% per year. We use this factor as default value in our scenario projections (see Figure 3-8 for the resulting curve in 2100), but will also discuss results using other material efficiency factors in Chapter 7.

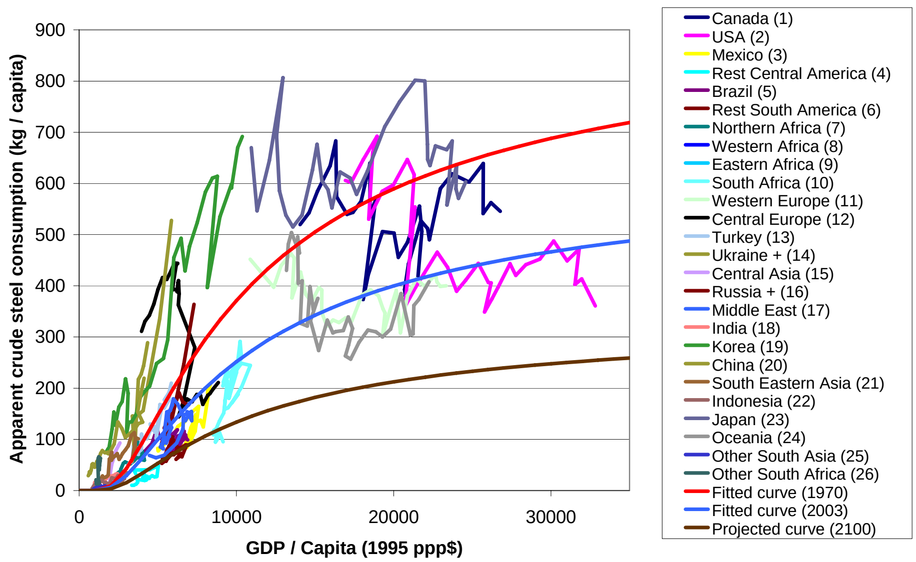

Figure 3-8 Fitted historical IU_{cap} curve and IU_{cap} curve used for projections

Based on the basic IU_{cap} curve given in Figure 3-8, we developed for each region specific IU_{cap} to fit the observed historical per capita consumption:

- For the five regions (Canada, USA, Western Europe, Japan and Oceania) having per capita income levels above 20000 1995 ppp $ in 2003, we kept the maximum in the intensity of use curve (parameter $-\beta$) equal to the basic curve. We calibrated the per capita saturation level (parameter α) in such as way that the resulting per capita consumption level in 2003 equals the per capita consumption level in 2003.
- For China and the Ukraine+ region, which currently have per capita consumption levels well above the fitted curve at per capita income levels far below 9000 1995 ppp $, we kept the per capita saturation level (parameter α) equal to the fitted curve. We calibrate the maximum in the intensity of use curve (parameter $-\beta$) in such a way that the resulting per capita consumption level equals the historical per capita consumption level in 2003.
- For Korea, currently having at a per capita income of 10000 1995 ppp $ already a per capita consumption above the saturation level predicted by the basic curve, we assume a final per capita saturation level (parameter α) equal to Japan. The maximum

[7] We assume the fraction of crude steel to be lost in the conversion from crude steel to finished steel to decline from approximately 10% to 5% (Section 4.4.4) and the amount of finished steel to be lost in the conversion from finished steel to final product to decline from 13% to 5%. This means that for an equivalent amount of final product, 13% less crude steel is required, equivalent to 0.15 % per year.

in the intensity of use curve (parameter –β) is than calibrated using the same method as used for China+ and the Ukraine+ region.

- For all other regions, we use the basic IU_{cap} curve. To avoid large deviations from historical data in the years following 2003, we calculate the absolute difference between the historical data and the basic IU_{cap} curve in 2003. In the years following 2003, this absolute difference is gradually decreased as a function of per capita income to a value of 0 at a per capita income of 20000 1995 ppp $.

A more detailed explanation is given in Appendix 4, where also the resulting values for parameters α and β are given.

3.4.2 Production and consumption of iron castings from foundries

In our model, we incorporate iron and steel foundries in a rather simple way. Based on the limited information from literature, we assume the foundry production to be a certain percentage of the crude steel consumption and we do not separately project the demand for cast iron products. Iron and steel foundries are only included in our model to have a complete overview of iron and steel flows for use in the material flow model. Energy use and CO_2 emissions related to foundry production are not included in the model. We use the ratio of foundry iron production compared to apparent crude steel consumption as derived for the US (Figure 3-7) for all regions. For the year 1900, the starting year of our analysis, we use a ratio of 0.4 for all regions. For unknown years we use linear interpolations. Between 1900 and 1938 (the first year for which a value is known), we also use linear interpolation. For the projections until 2100, we use the ratio for 2003 (0.08) as constant ratio for all years for all regions.

4 Steel production and trade flows

4.1 Conceptual modelling approaches

4.1.1 Introduction

To model regional energy demand and CO_2 emissions associated with the production of steel, not the steel demand as discussed in the previous chapter, but the production of steel per technology is the important variable. To accurately project energy use and CO_2 emissions, one would ideally like to model:

1. The technologies that have been and will be applied in the various process steps given in Figure 2-1.
2. The regions in which the various process steps will take place, i.e. trade flows of various commodities in the production chain of finished steel products.

From an energy point of view (Section 2.3), the most critical technology choice is the choice between steelmaking routes using primary iron derived from iron ore as input and routes using scrap as iron input. If we neglect the outdated open-hearth furnace that is expected to disappear completely in the coming years (Hidalgo et al., 2005), we can distinguish between three currently applied primary and one secondary route for steelmaking:

1.1 Pig iron (produced by smelt reduction) – Basic oxygen furnace (primary route)
1.2 Pig iron (produced by blast furnaces) – Basic oxygen furnace (primary route)
2. Direct Reduced Iron – Electric arc furnace (primary route)
3. Scrap – Electric arc furnace (secondary route)

In Section 4.1.2, we discuss existing modelling approaches related to projecting the choice between these routes and in Section 4.2 we give historical trends. If we want to project crude steel production based on a certain level of apparent crude steel consumption (previous chapter), it is necessary to model the international trade in:

1. Semi-finished and finished steel products

In Section 4.1.2, we discuss existing modelling approaches related to project steel trade. Historical trends are presented in Section 4.2. Even if the steel production by technology is accurately modelled based on steel demand and steel trade, there are other trade flows that influence the specific regional energy demand and CO_2 emissions of the iron and steel industry per tonne of steel produced such as the trade in:

2. Aggregated iron ore (ore pellets from sinter plants).
3. Cokes.
4. Primary iron (pig iron or direct reduced iron).

These trade flows are not explicitly included in any of the model discussed in Appendix 2 and we therefore do not discuss existing modelling approaches. Below, we briefly discuss the influence of these trade flows on the regional energy demand and CO_2 emissions.

Sintering and pelletisation of iron ore takes place either close to the iron ore mines or at the location of the blast furnace. *"Pellets are nearly always made of one well-defined iron or concentrate at the mine... Sinter is generally produced at the ironworks from pre-designed mixtures of fine ores, residues and additives" (Hidalgo et al., 2003).* Cokes are also not always produced in the same region where they are produced. The EU-15 in 2003, for example, imported 6.5 Mt of coke (net import) on a total consumption of 37 Mt (Ameling and

Lüngen, 2004). The location of sintering, pelletisation and coke plants relative to the steel production influences the specific energy consumption related to steel production in a given region. Given the relative small specific energy use of ore agglomeration and coke making compared to primary iron production (typically less than 10%), the relative error made in neglecting these trade flows is, however, small.

In basic oxygen furnaces using pig iron, the production of primary iron and the production of steel are by definition coupled in an integrated plant, so iron and steel production always take place in the same region. In the production of steel in electric arc furnaces using a primary iron source, however, the production of steel is not necessarily integrated with the production of primary iron (either PI or DRI). It is therefore possible that the production of iron and the production of steel produced from this primary iron take place in different regions. It might be advantageous for regions with large iron ore reserves (e.g. South America and Oceania) to create some value added to their natural iron ore reserves by reducing it to iron before shipping[8]. An example of such a plant is the DRI/HBI plant in Port Hedland, Australia (Steel Technology.com, 2005) producing 100% for export purposes, resulting in a primary iron production exceeding the production of steel in Oceania since 1999 as we will show in the overview of historical trends. On a regional level, these trade flows can therefore have quite some influence. We will, however, not include the primary iron trade within our model.

4.1.2 Existing modelling approaches for steel trade and steel production by technology

In projecting steel trade and the shares of various technologies in the total steel production of a region, three methods are used:

1. Changes in steel trade or technology shares are driven by differences in production costs between regions or technologies
2. Changes in steel trade or technology shares are driven by an analysis and extrapolation of historical trends
3. Changes in steel trade of technology shares are driven by some exogenous assumption on the development of steel trade and technology shares as function of time or another variable.

Of the models summarised in Appendix 2, Hidalgo et al. (2005), Gielen and Moriguchi (2002) and Mannaerts (2002) use the first method to project steel trade, although the models differ widely in the level of detail included in the cost functions. These models also use production cost differences between technologies to project the share of certain technologies in total steel production, an approach also taken by van Vuuren et al. (1999), Das and Kandpal (1998) and Gielen and van Dril (1999).

The major advantage of using this method to project steel trade and technology shares is the explanatory power of the drivers resulting in changes. If a certain technology or a certain region is cheaper than another one, it will gradually take over production. However, there are a number of difficulties associated with this approach:

- The cost functions for a certain technology in a certain region consist of a wide variety of elements (fixed costs, variable costs, transport costs, trade barriers etc.), which are already difficult to specify accurately for one specific region in one specific historical year. Projection of these cost functions for multiple regions (in case of TIMER, 26 regions) for the coming 50 or 100 years is even more complex. Still, macro-economic assumptions on the development of labour, capital and energy costs

[8] Another advantage is the decrease in weight between iron ore and iron. The weight of pure iron (Fe) is only 70% of the weight of iron ore (Fe_2O_3).

can give an idea on the comparative advantages of one region over another, everything else (e.g. government policies) being equal. When keeping the limitations of the approach in mind, this can therefore still be a very useful approach.

- A wide variety of different semi-finished and finished steel products are traded internationally as well as certain intermediate commodities such as cokes, aggregated ores and primary iron. To accurately project these trade flows, separate production cost functions for all products should in principle be included in the model[9].
- Production costs differences are not the only driver behind material trade. Others are for example the investment climate of a region, the knowledge base for a certain region, the availability of scrap, government policies, the presence of other industries linked to the steel industry and comparative advantages in other areas (e.g. the absence of strict environmental regulations). It is difficult to differentiate these drivers in a quantitative way between regions.

As an example of the difficulties associated with production cost function modelling, we would like to note that none of the models given in Appendix 2 explicitly includes scrap availability as a driver influencing the share of secondary steel, e.g. by modelling the influence of scrap availability on scrap prices, whereas intuitively, scrap availability is probably one of the most important explanatory variables for the shares of primary versus secondary technologies.

Probably as a result of these difficulties, other modellers take the more simple second approach by just assuming certain trade flows and technology shares based on past trends. Of the models summarised in Appendix 2, this is done by Michaelis and Jackson (2000) and in the VLEEM model (2005) for both steel trade and technology shares and by Das and Kandpal (1998) only for steel trade.

An interesting attempt to couple steel trade to an exogenous variable (per capita income) is given by Wienert (1996), although he does not use his analysis to project steel trade towards the future. Based on a detailed worldwide historical analysis for the period 1960-1993, he derives the general pattern of steel trade as a function of per capita income:

- *'With beginning industrialisation the steel import grows so fast that an increase in local production becomes profitable. To increase production capacity, time is required and capacity increase cannot keep up with the increasing consumption, resulting in an even larger net import.*
- *When the increase in steel consumption becomes smaller as a result of decreasing speed of the industrialisation process, the net import declines and the country eventually becomes as net steel exporter.*
- *Without a strongly increasing consumption, further capacity increase becomes so risky and normally does not take place. This results in effects on the profitability, because the use of technological progress for productivity gains is not equally possible in existing plants as in new plants. When the steel consumption finally declines, the costs are driven up by low load factor and closure of plants. Because the steel consumption in highly developed countries remains higher than in the developing countries that follow them, it becomes profitable for the latter to penetrate the markets of the developed countries by opening e.g. sales offices. As a result of all these influences, the net export of a country in view of this idealised development process becomes smaller or is even replaced by a net import'*[10].

A graphical representation of this development is given in Figure 4-1.

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[9] Especially since the difference in export price between various semi-finished steel products can easily differ by as much as a factor 4 (Gielen and van Dril, 1997, pp. 82).
[10] Translated from German (Wienert, 1996a).

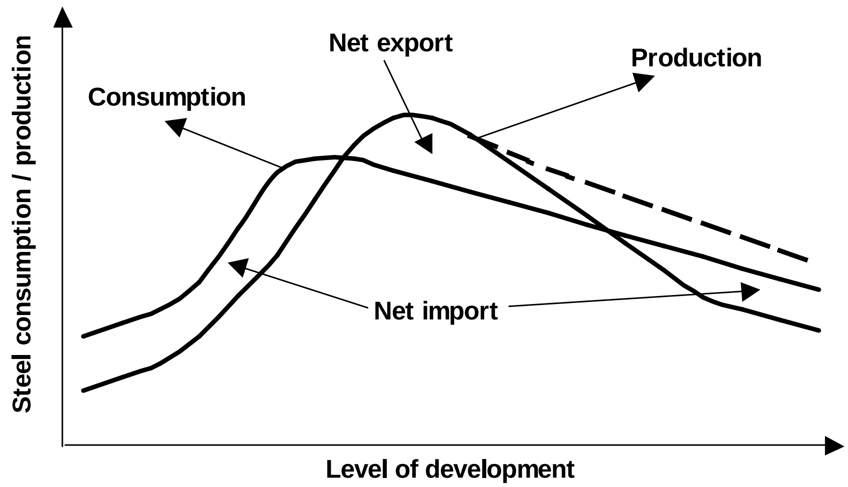


Figure 4-1 **Development of steel use and steel production as function of level of development (based on Wienert, 1996a).**

4.2 General description of modelling approach

The approach used in our model to project steel trade, steel production and technology choice has the following characteristics:

- Steel trade is not modelled using production cost functions, but is included via exogenous trade scenarios based on historical trends and a narrative storyline.
- The future availability of scrap is modelled using a detailed material flow model taking into account product and lifetime distributions.
- The modelled availability of scrap is used to determine the shares of the three routes distinguished in Section 4.1.1.

An overview of the material flow model used is shown in Figure 4-2, including flows (starting with F), trade flows (TF), commodities (C) and ratios determining the split between certain flows. Below we give a narrative description of the material flow model. The basis of the model is the apparent consumption of semi-finished and finished products (*F17*), expressed in crude steel equivalents. This demand is projected via the method described in the previous chapter. Consumption can either be met by domestic production (*F13*), but can also be imported from other regions (*TF3*). This steel trade is projected based on exogenous trade assumptions.

In the production of finished and semi-finished products, a fraction of steel is lost in the form of circulating scrap (*F14)*. Part of the circulating scrap is recovered and used as input into steelmaking (*F3*). Semi-finished and finished steel products are used by the steel converting industries to produce steel containing end products (*F20*). In this process, again a fraction of steel is lost in the form of prompt scrap *(F18),* recovered to a certain extent to be used in steelmaking (*F2*). The end products are used in the economy. We distinguish between four product groups with different lifetime distributions based on literature information. At the end of their economic lifetime they become available as obsolete scrap (*F22*). The end products can of course be exported to other regions, both directly after production *(TF4)* or after their economic lifetime[11] *(TF5*). In our model, we do not take these trade flows into account. The obsolete scrap is partly recovered for use in steelmaking.

[11] For example the trade with second-hand cars.

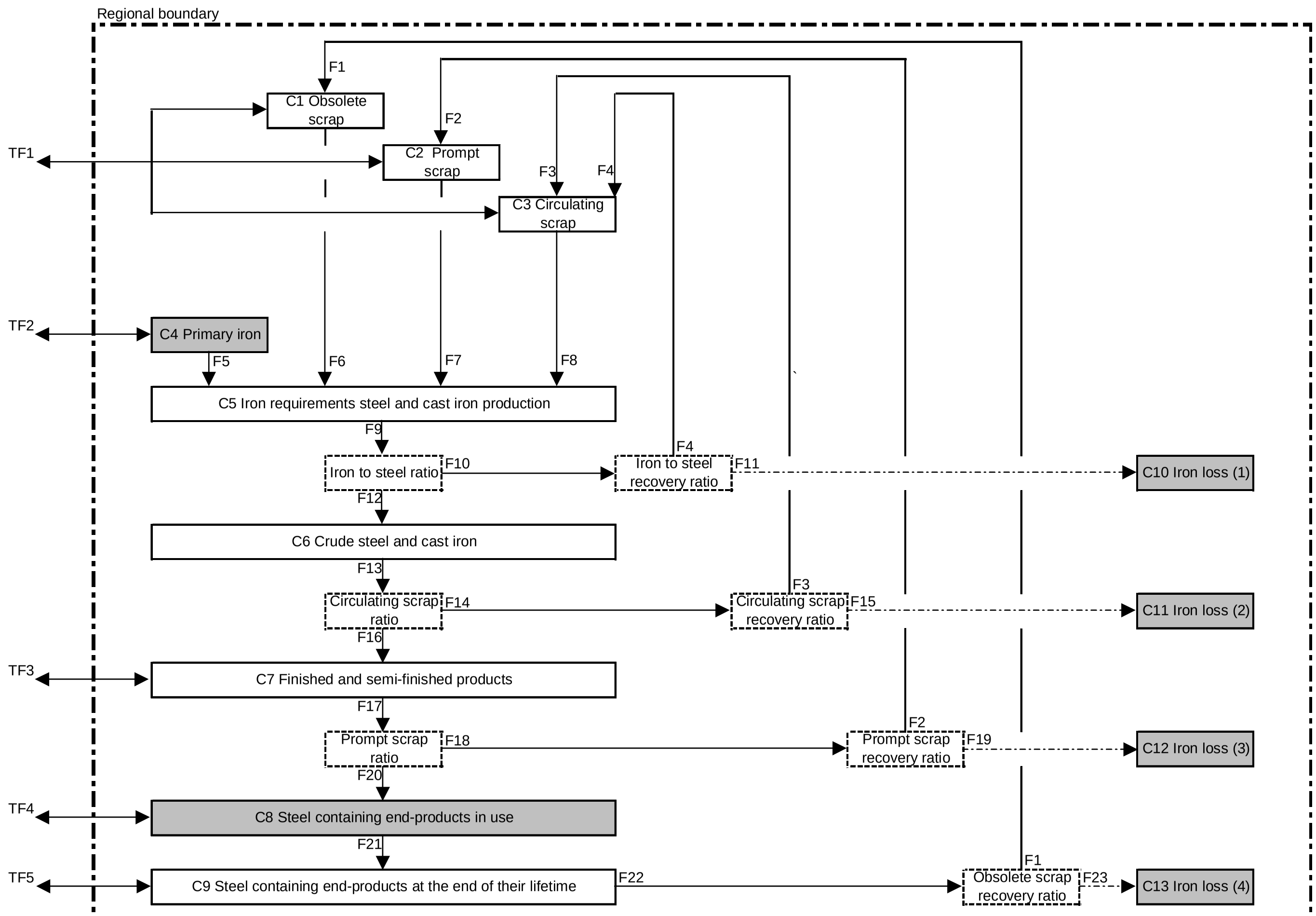


Figure 4-2 **Overview of the material flow analysis**

Scrap is also traded (*TF1*). This trade is included in the model (i.e. the flows are there), but in the current model versions, scrap trade is set to 0 in the projections. Since not all scrap is recovered and since there is a substantial time gap between the production of steel containing products and their occurrence as obsolete scrap, the total availability of scrap is not sufficient to meet total iron demands for steelmaking. The additional iron inputs are in the form of primary iron (*F5*). As discussed above, primary iron can also be traded (*TF2*). This trade is not included in the model. In steelmaking and in the production of iron castings, some of the iron input is already lost (e.g. in the form of slag, *F10*). Parts of these iron losses are recovered as circulating scrap (*F4*). For the calibration of model parameters and as input for the trade scenarios, we first analyse past trends for:

- Production and trade of steel (Section 4.3.1)
- Production of steel by technology (Section 4.3.2)
- Specific iron requirements per tonne of crude steel (Section 4.3.3)
- Production and trade of primary iron (Section 4.3.4)
- Availability and recovery of circulating scrap (Section 4.3.5)
- Availability and recovery of prompt scrap (Section 4.3.6)
- Availability and recovery of obsolete scrap (Section 4.3.7)
- Scrap trade (Section 4.3.8)

These historical trends are translated into model parameters. Together with a detailed model description, these are given in Section 4.4.

4.3 Overview of past trends and data used for estimating model parameters

4.3.1 Production and trade of steel

Steel production in the various TIMER regions is shown in Figure 4-3.

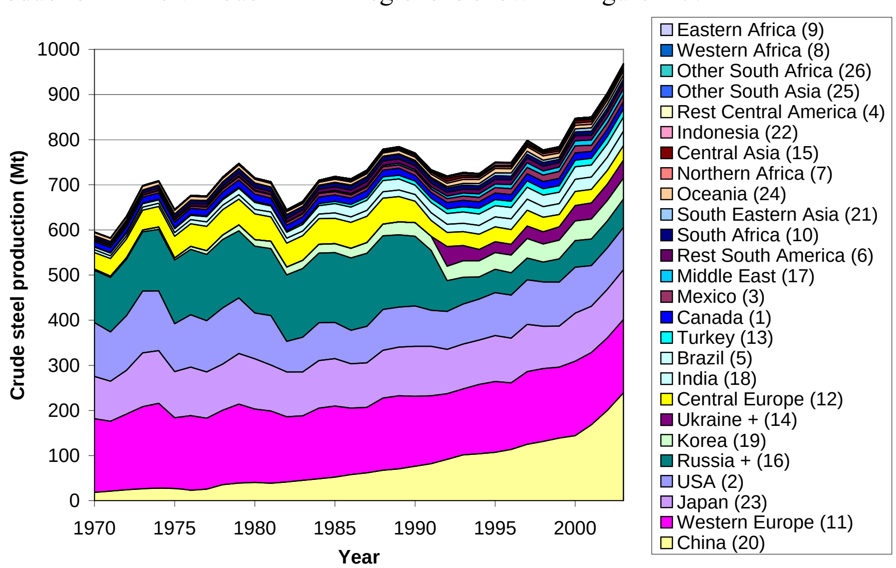


Figure 4-3 **Crude steel production from 1970-2003 in the 26 TIMER regions in the order of decreasing production in 2003 (IISI, Various years). Before 1992, Baltic states (part of Region 12), Ukraine + (Region 14) and Central Asia (Region 15) are within Russia+ (Region 16).**

Overall, consumption of steel and production can differ substantially. The net export of steel in crude steel equivalents is calculated by deducting the apparent crude steel consumption (Figure 3-3) for a given region from the crude steel production (Figure 4-3). We give an

overview for all TIMER regions in Table 4-1 for 1970 and 2003. In Figure 4-4, we give time-series for 1970-2003 for those regions having a net export of +/- 10 Mt in at least one of the years shown. In relative terms, we show the net export as function of domestic consumption in Figure 4-5 as function of per capita income.

Table 4-1 Consumption, production and net export of steel in the 26 TIMER regions in 1970-1972 and 2001-2003 (IISI, Various years)

	1970				2003			
Region	**Cons.**	**Prod.**	**Net export**	**Net export[1]**	**Cons.**	**Prod.**	**Net export**	**Net export[1]**
	Mt			**%**	**Mt**			**%**
Canada (1)	11.1	11.2	0.1	1%	17.3	15.9	-1.4	-8%
USA (2)	127.3	119.3	-8.0	-6%	103.9	93.7	-10.2	-10%
Mexico (3)	4.2	3.9	-0.3	-7%	21.0	15.2	-5.8	-28%
Rest Central America (4)	0.4	0.1	-0.3	-66%	2.5	1.4	-1.1	-45%
Brazil (5)	6.1	5.4	-0.7	-11%	17.3	31.1	13.9	80%
Rest South America (6)	7.5	3.8	-3.8	-50%	12.1	11.9	-0.2	-1%
Northern Africa (7)	2.6	0.6	-2.0	-77%	9.9	6.5	-3.4	-34%
Western Africa (8)	0.7	0.0	-0.7	-100%	2.4	0.1	-2.3	-97%
Eastern Africa (9)	0.0	0.0	0.0	-	0.9	0.1	-0.8	-94%
South Africa (10)	4.8	4.8	0.0	-1%	4.6	9.5	4.9	108%
Western Europe (11)	158.7	163.4	4.7	3%	157.2	162.4	5.2	3%
Central Europe (12)	35.9	36.9	1.0	3%	27.2	32.7	5.4	20%
Turkey (13)	1.8	1.3	-0.5	-26%	15.3	18.3	3.0	19%
Ukraine + (14)	-	-	-	-	18.6	39.4	20.8	112%
Central Asia (15)	-	-	-	-	1.6	5.4	3.8	238%
Russia + (16)	-	-	-	-	27.4	62.7	35.3	129%
Middle East (17)	4.5	0.1	-4.4	-98%	31.4	13.4	-18.0	-57%
India (18)	6.4	6.3	-0.2	-2%	35.0	31.8	-3.2	-9%
Korea (19)	3.5	2.7	-0.8	-24%	47.6	46.6	-1.0	-2%
China (20)	24.9	18.6	-6.2	-25%	286.4	238.9	-47.5	-17%
South Eastern Asia (21)	3.6	0.5	-3.0	-86%	32.8	9.2	-23.6	-72%
Indonesia (22)	0.6	0.0	-0.6	-98%	5.2	2.0	-3.2	-61%
Japan (23)	69.9	93.3	23.4	34%	77.0	110.5	33.5	43%
Oceania (24)	7.2	7.0	-0.2	-3%	10.1	8.4	-1.7	-17%
Other South Asia (25)	0.7	0.0	-0.7	-100%	3.3	1.0	-2.2	-68%
Other South Africa (26)	2.0	0.4	-1.6	-78%	1.9	0.2	-1.7	-92%

[1] As percentage of crude steel consumption

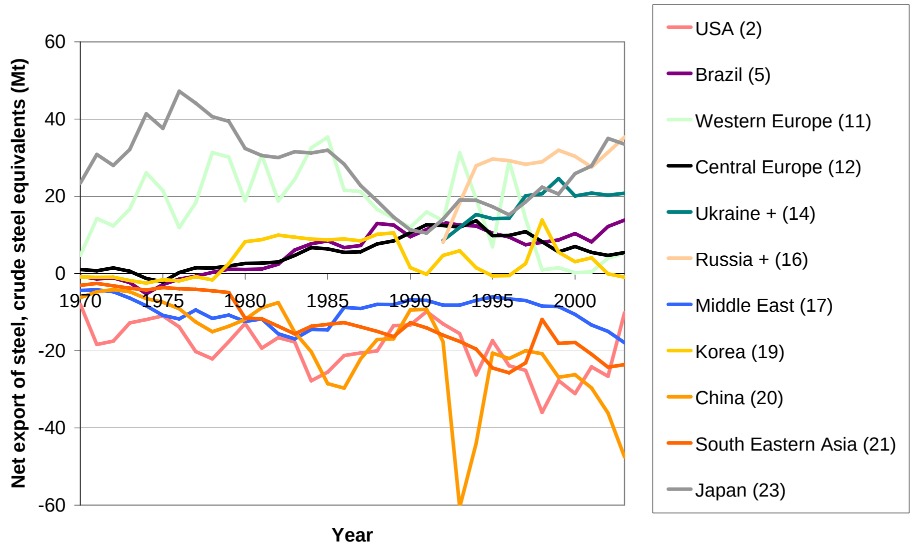


Figure 4-4 **Net export of crude steel from 1970-2003 in TIMER regions having a net export exceeding +/- 10 Mt / year in at least one of the years shown. Ukraine+ (region 14) and Russia+ (region 16) only shown from 1992 onwards.**

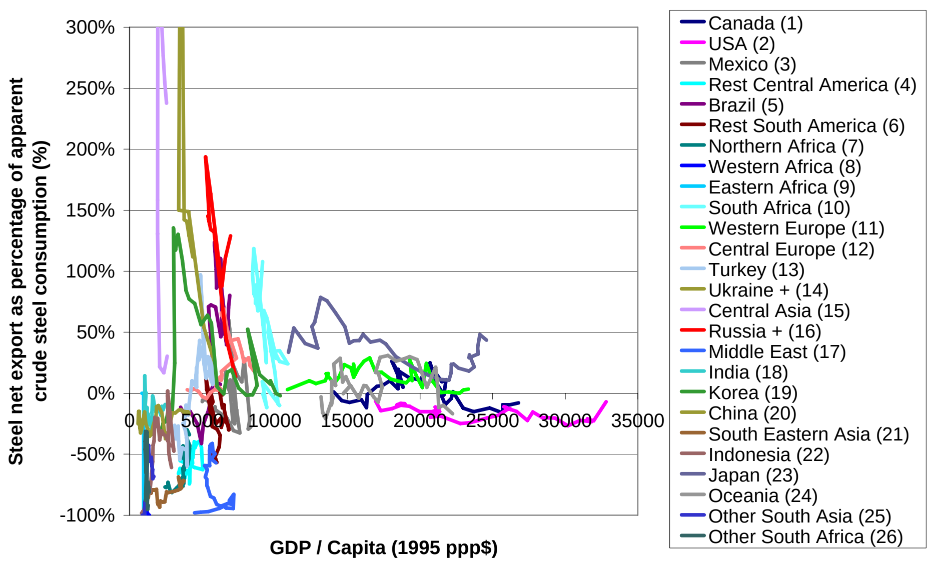


Figure 4-5 **Net export of crude steel as percentage of the apparent crude steel consumption in the TIMER regions. Regions from the former USSR (region 14, 15 and 16) only shown from 1992 onwards.**

From the table and figures, we draw the following conclusions:

- The net export as percentage of crude steel consumption differs widely from region to region. In 2003, steel export as percentage of apparent crude steel consumption ranges from –97% (Eastern Africa) to +238% (Central Asia).
- With the exception of the former centrally planned economies (region 12 and 14-16), the generalised pattern identified by Wienert (1996a) and shown in Figure 4-1 seems to be confirmed by the empirical data. Less developed regions generally have a considerable net import of steel. The net import declines when per capita income

increases and some regions (Brazil, South Africa, Turkey and Korea) have become net exporters in the course of their development[12].

- In developed regions (Canada, USA, Western Europe, Japan and Oceania), steel production and consumption are in general relatively balanced (net export less than +/- 20% of crude apparent crude steel consumption) with the exception of Japan that still has a net export of 43% of apparent crude steel consumption in 2001-2003.
- The former centrally planned economies (12 and 14-16) are all net exporters in the period 2001-2003. After the transition in the beginning of the 1990-ies, apparent crude steel consumption declined significantly[13] and as a result, these regions have a significant overcapacity.
- Two single country regions (Brazil and South Africa) are also significant net exporters of steel. According to Wienert (1996a), this can for Brazil be explained by a combination of wrong government planning and the presence of large iron ore reserves. The latter is also true for South Africa.

From Figure 4-4 and Figure 4-5 it is hard to draw overall conclusions about the relative amount of interregional steel trade as percentage of domestic *worldwide* consumption over time. The International Iron and Steel Institute (Various years) reports steel trade as percentage of world steel production (Figure 4-6), in crude steel equivalents[14]. For regional energy demand modelling, these reported values are, however, of limited value for two reasons:

- The figures are absolute trade figures and not net trade figures. It is therefore difficult to use them to monitor developments in the ratio between production and consumption of steel. Increased specialisation within the steel industry might for example lead to more trade (both export and imports), but not necessarily to more net trade (exports – imports).
- The figures are trade flows between countries and therefore also include intraregional trade. Trade flows between countries of the former USSR are therefore included after 1992, but not in the years before. The European Union is responsible for about 1/3 of all steel exports, but to a large extent these exports are to other countries within the European Union.

We therefore show in Figure 4-6 also the net interregional trade for the TIMER regions as percentage of world steel production for the period 1992-2003. Although it is difficult to draw robust conclusions as a result of the relative short time-series we can conclude that there are no indications that the net interregional trade has increased significantly in the period 1992-2003.

[12] If we consider all regions except Canada, USA, Western Europe, Japan and Oceania as less developed regions and exclude the formerly centrally planned economies (region 12 and 14-16), we can conclude that all regions except Mexico (region 3) and Other South Africa (region 26) experienced a declining net import between 197-1972 and 2001-2003 (Table 4-1).

[13] Apparent crude steel consumption in the former USSR (region 14-16) was 153 Mt in 1990 and 48 Mt in 2003. In Central Europe (region 12), steel consumption in 1990 was 37 Mt in 1990 and 27 Mt in 2003 (IISI, Various years).

[14] Total exports of semi-finished and finished steel products are multiplied with a constant factor of 1.3 to obtain crude steel equivalents. Using this constant of 1.3 makes no allowance for yield improvement, thus leading to increasing overestimation of the export share. In the statistical yearbook of 2005, steel trade as percentage of world steel production is no longer reported, probably because of the limited usefulness of the figures.

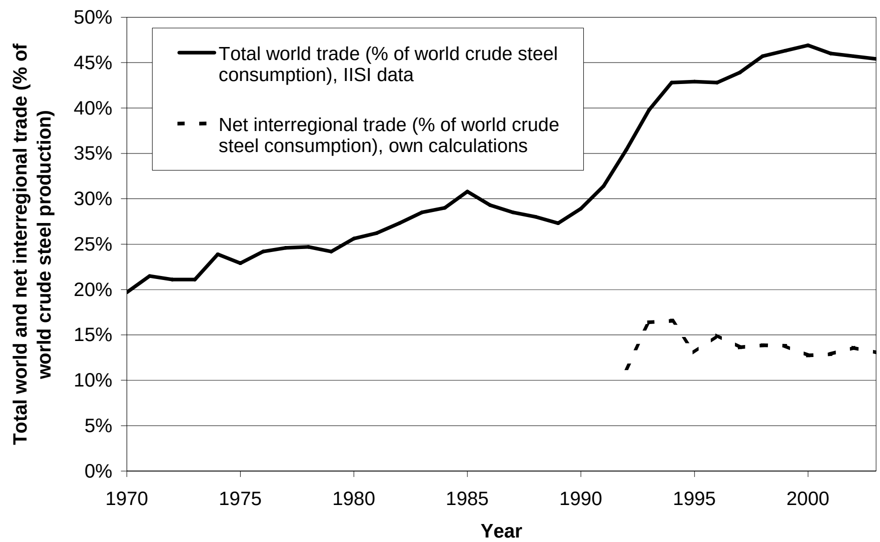


Figure 4-6 **Total world and net interregional trade as percentage of world steel production. Data for interregional trade only shown after 1992**

4.3.2 Production of steel by technology

The worldwide shares of basic oxygen furnace (BOF), electric arc furnace (EAF) and open-hearth furnace (OHF) steelmaking in the total steel production in 1990 and 2003 are shown in Figure 4-7, regional data in Figure 4-8. Figure 4-8 reveals that the shares of the various technologies in total production differ significantly from region to region. The share of the OHF process went down in all regions. In 2003, the process was still used in India, the regions of the former USSR and Central Europe. Worldwide, not more than 4% of the total crude steel production in 2003 was produced using this process, whereas in 1990, the share was still 15%. The shares of the BOF and the EAF processes in 2003 ranged from 0% to 100. Worldwide, 64% of steel in 2003 was produced via the BOF process and 33% via the EAF process. In 1990, these percentages were 55 and 28% respectively.

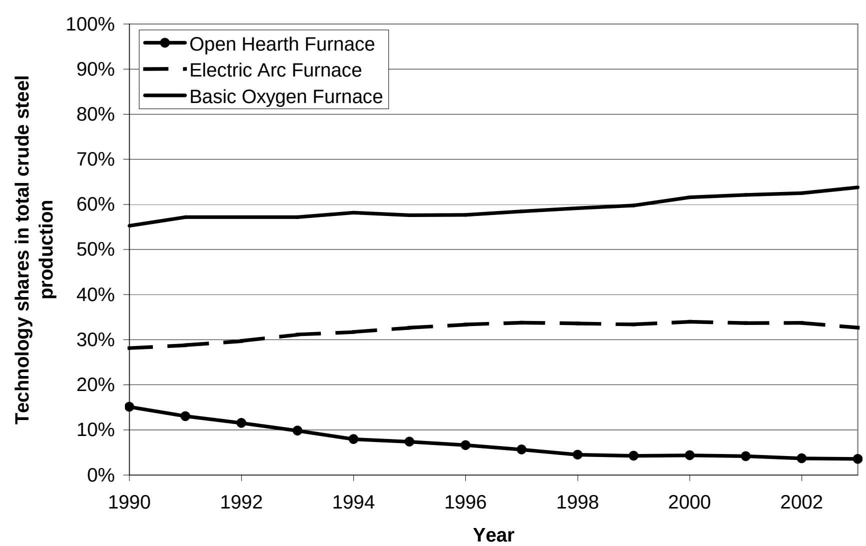


Figure 4-7 **Worldwide technology shares between 1990 and 2003**

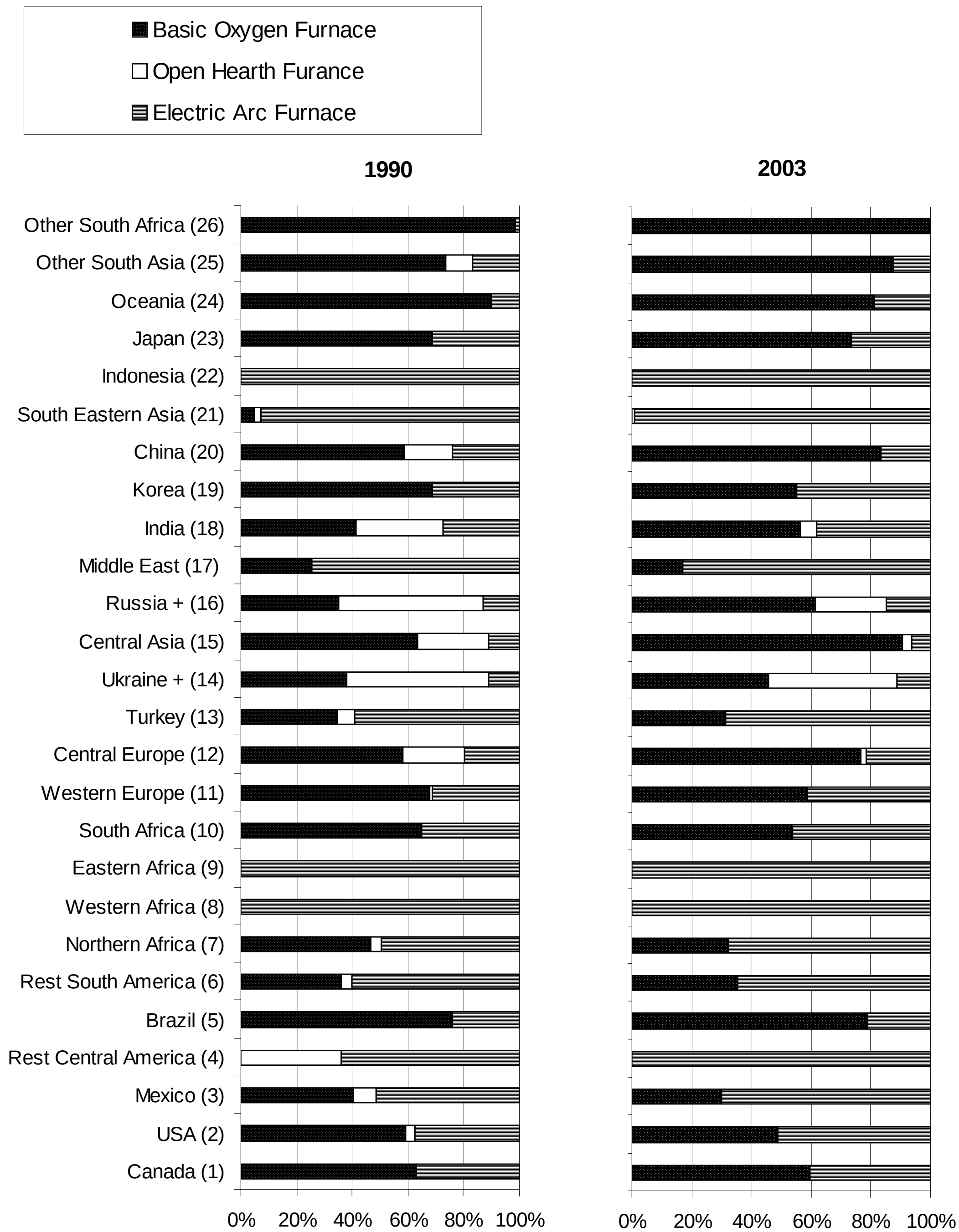


Figure 4-8 **Technology shares in TIMER regions in 1990 and 2003. Data for Ukraine+, Central Asia and Russia+ are for 1992 and 2003**

4.3.3 Specific iron requirements per tonne of crude steel

Decisive statistical data on total scrap consumption for the production of crude steel and iron castings is not available. To derive scrap consumption based on the production of crude steel and iron castings and the production of primary iron, one first needs to know the total specific iron requirements per tonne of crude steel. Crude steel production in the statistics of the International Iron and Steel Institute used to be defined as the total output of usable ingots, continuously cast semi-finished products and liquid steel for castings (IISI, 1990), although no definition is given anymore in the most recent version of the statistical yearbook. Some metal is lost in the conversion of liquid steel to crude steel and the total iron requirements therefore exceed the crude steel production. Detailed data on the total iron requirements per tonne of crude steel can be found in the balances prepared by World Steel Dynamics (WSD, 2005). They distinguish between liquid steel (before casting) and crude steel (after casting) and use the ratios for the US in 1975 and 2003 given in Table 4-2. The metallics inputs given in the table are not corrected for the fact that pig iron (main input into open-hearth and basic oxygen furnaces) has an iron content of approximately 96%.

Table 4-2 Liquid to crude steel and total metallics to liquid steel ratios used for the US by World Steel Dynamics (2005).

	1975	2003
Steelmaking		
Liquid steel / crude steel (ingot casting)	1.045	1.045
Liquid steel / crude steel (continuous casting)	1.030	1.030
Total metallics / liquid steel (OHF)	1.200	1.200
Total metallics / liquid steel (BOF)	1.170	1.140
Total metallics / liquid steel (EAF)	1.111	1.060
Foundry production		
Total metallics / foundry production	1.500	1.500

Of the liquid steel not embodied in the cast crude steel, 60% is assumed to be recovered as circulating scrap (next section), but no recovery is assumed for the metallics not embodied in the production of liquid steel. For foundries, 90% recovery is assumed for the metallics not embodied in the foundry products. The ratios used by World Steel Dynamics are reasonably in line with a few other sources that could be found. Wienert (1996b) mentions an iron input per ton of crude steel of 1.15. In Moll et al. (2005), a total input of 92.4 Mt of pig iron and 17.0 Mt of scrap is mentioned in Basic Oxygen Furnaces in the EU-15 in 2000 for a crude steel production of 98.3 Mt, equivalent to a metallics input of 1.11 tonne per tonne of crude steel.

Some other sources, however, give lower estimates for the total iron consumption per tonne of crude steel. In Moll et al. (2005), a scrap input of 67.0 Mt in electric arc furnaces is reported for a crude steel production of 64.8 Mt, equivalent to a metallics input of 1.03 tonne per tonne. In a study by the American Iron and Steel Institute (AISI, 2001), the total iron contained in by-products such as dust, sludge, slag etc. is estimated at 3.24 Mt on a total crude steel production of 95.26 Mt. This is equivalent to a metallics input of 1.03.

4.3.4 Production and trade of primary iron

The production of pig iron in the TIMER regions in 1970-2003 is shown in Figure 4-9. Almost all pig iron is produced by blast furnaces. The only commercially applied smelt reduction process for the production of pig iron is the COREX/FINEX process applied in three plants worldwide (Wieder et al., 2004), having a total yearly capacity of approximately 3 Mt/year:

- Saldanha Steel, saldanha works, South Africa (capacity of 650 kt/year), coupled with a 800 kt/year Direct Reduced Iron unit using the smelt reduction export gas.

- Jinal Vijayanagar steel, Torenagallu Works, India (two modules, each having a capacity of 800 kt/year), export gas used for power generation, a pellet plant and as a fuel in the integrated plant complex.
- Posco, Pohang Works, South Korea (capacity 800 kt/year).

Another process close to commercial application is the HIsmelt process. A commercial scale plant (capacity of 800 kt/year) is currently being constructed in Australia, was expected to start up in late 2004 and to reach full production in the first half of 2006 (Rio Tinto, 2002).

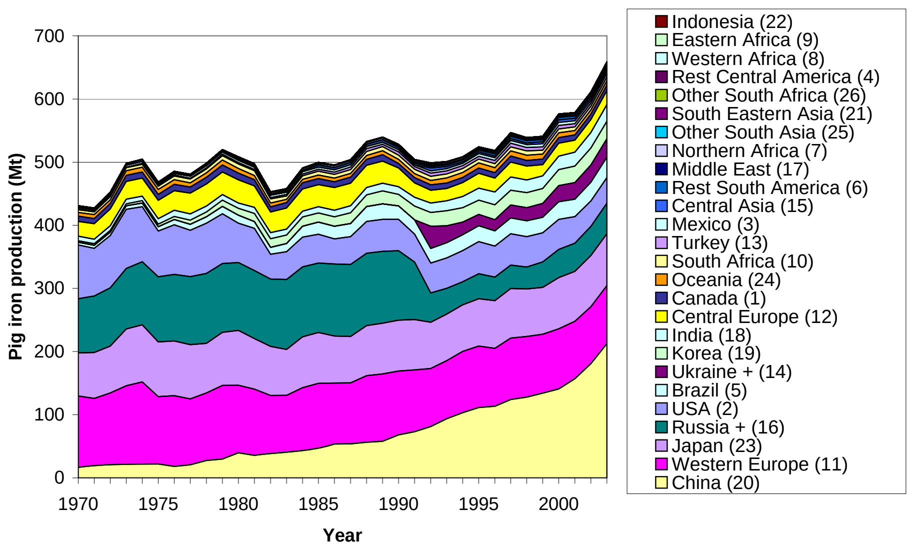


Figure 4-9 **Pig iron production from 1970-2003 in the 26 TIMER regions in the order of decreasing production in 2003 (IISI, various years). Before 1992, Baltic states (part of Region 12), Ukraine + (Region 14) and Central Asia (Region 15) within Russia+ (Region 16).**

We show an overview of international pig iron trade in Table 4-3 (IISI, various years). There are clearly shortcomings in the trade data, because total import and total export figures do not match well, which would ideally be the case. The numbers are consistent with numbers given by Cattell et al. (2002, slide 6), who estimates the exports of merchant pig iron between 1992 and 2001 to fluctuate between approximately 10 and 14 Mt. Two countries, Brazil and Russia dominate the merchant pig iron market with specialised production for exports. Both countries export approximately 4 Mt of pig iron each year with Brazil, very generally stated, supplying the United States and Russia supplying Europe and Asia (Moore and Aylen, 2002).

Table 4-3 **Worldwide trade in pig iron**

Values in Mt	**Export**			**Import**		
	2000	**2001**[1]	**2002**	**2000**	**2001**	**2002**
Europe	0.4	*0.4*	0.5	3.1	3.0	2.8
Former USSR	3.6	*5.8*	4.6	-	-	-
Northern America	0.2	*0.2*	0.1	5.1	4.5	4.7
Central / South America	4.1	-	4.4	1.4	1.0	1.1
Asia	3.9	*1.5*	1.5	4.8	2.5	2.4
Africa	1.0	-	0.4	-	-	-
Total	13.1	*8.0*	11.6	14.3	10.9	10.9

[1] Export figures most probably wrong, because both Brazil and South Africa exported pig iron

The production of DRI/HBI is shown in Figure 4-10. The gas based MIDREX process is the dominant technology in DRI/HBI production, covering 65% of total production in 2003. Other gas-based processes (e.g. HYL I, HYL III and Finmet accounted for 25% and coal based processes accounted for 10% in 2003 (Midrex, 2003). The Figures reveal that the production of DRI/HBI is concentrated in Central and South America, the Middle East and South Asia (India), together responsible for more than 70% of DRI/HBI production.

According to Daniels (2002, pp. 34), the "*Capacity of the Midrex process (gas-based) concentrates in areas where cheap natural gas is available as a by-product of oil production. Generally, in these areas without a market for the gas, the gas is flared. Often, it profits from the presence of ore, too*"

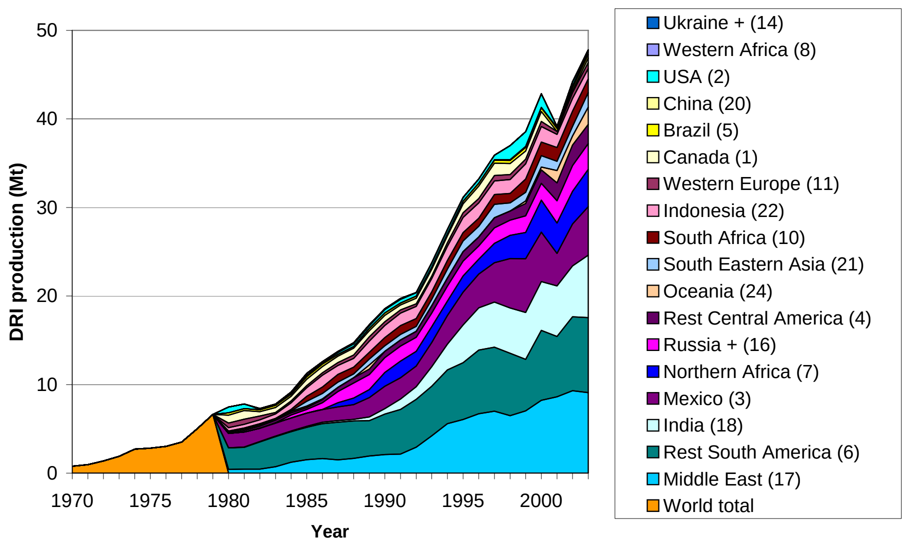


Figure 4-10 Production of DRI from 1970-2003 in the 26 TIMER regions (Midrex, 2003). Until 1980, only the worldwide total is available.

Worldwide trade of DRI/HBI amounted to 12.3 Mt in 2003 (Midrex, 2003), which is about one quarter of total DRI/HBI production. In 1998, the major trade flow was from Central/South America to the United Sates and Asia (in total approximately 3 Mt), from Russia to various other regions (0.7 Mt) and from Malaysia and India to other Asian countries (1.6 Mt) (UN, 1999). Since 1998, two large export-oriented plants came on stream in Venezuela and Australia (total capacity 4.4 Mt) (Midrex, 2003).

The total production of primary iron as percentage of total worldwide crude steel production is shown in Figure 4-11 for the period 1900-2003. Worldwide the ratio of primary iron production over crude steel production is remarkably constant since 1960, varying only between 70 and 75% in this period. In the years before, the primary iron to crude steel ratio was higher, because of a lower availability of obsolete scrap and also because of a larger fraction of iron castings compared to crude steel production (Section 3.3.2). In Figure 4-12, the production of primary iron in the TIMER regions in 2003 is given as percentage of the total crude steel production.

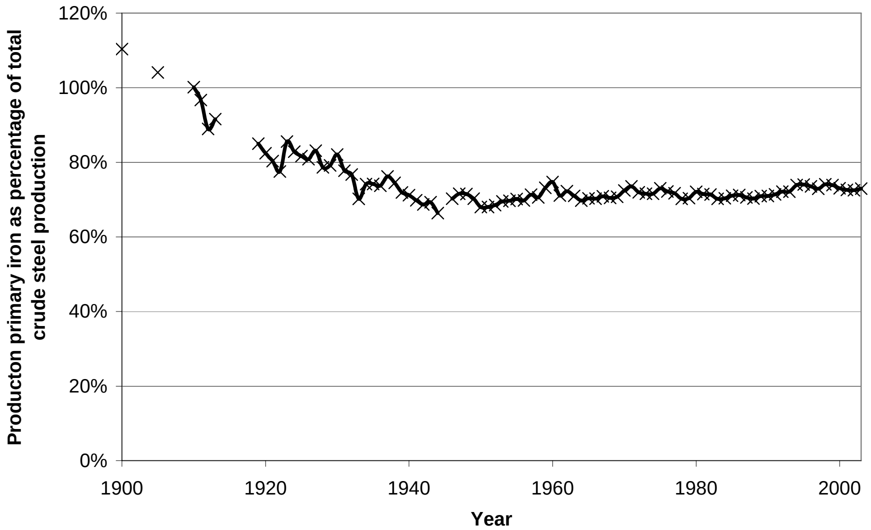


Figure 4-11 **Worldwide primary iron production (pig iron and direct reduced iron) as percentage of total crude steel production based on IISI (Various years), Midrex (2003) and Wirtschaftvereinigung Stahl (2004).**

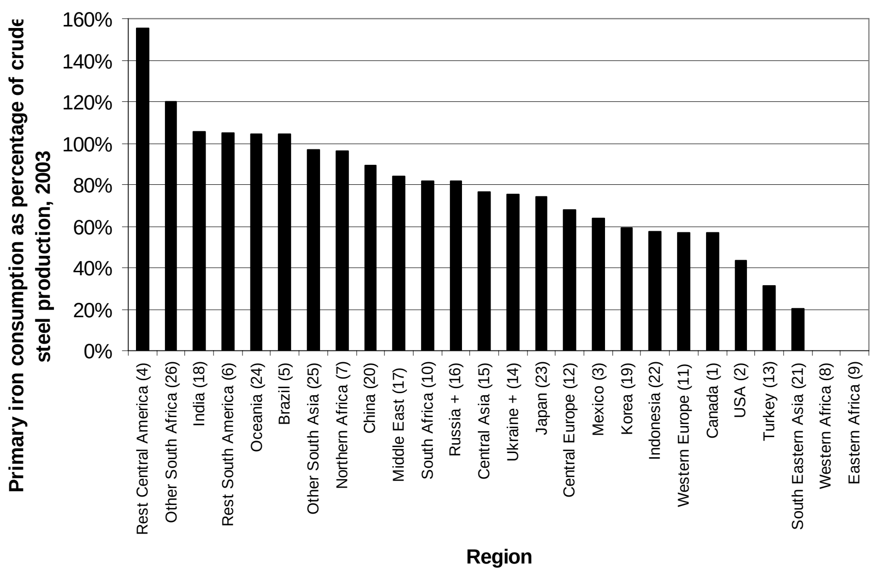


Figure 4-12 **Production of primary iron as percentage of total crude steel production in the TIMER regions in 2003.**

Figure 4-12 makes clear that regional differences are substantial with a range from 0% (Western and Eastern Africa) to 155% (Rest Central America). Percentages above 100% can be explained by a number of factors:

- The total iron input per tonne of crude steel is approximately 1.1 (Section 4.3.3).
- Some primary iron is also consumed for the production of iron castings.

- The figures refer to primary iron *production* as percentage of crude steel production. Countries with substantial net export of primary iron (e.g. Australia, Trinidad and Tobago, Venezuela) therefore have ratios above 100%.
- The data quality for especially some of the smaller regions (e.g. Other South Africa) is insufficient to calculate the percentage with sufficient accuracy.

In our model, we distinguish between the three routes for steelmaking given in Section 4.1.1 and to do so, it is necessary to split the steel production via the electric arc furnace route (Figure 4-8) into primary iron and scrap based electric arc furnace production. The worldwide direct reduced iron production as percentage of the total electric arc furnace steel production is shown in Figure 4-13 for 1990-2003 and regional shares are shown in Figure 4-14.

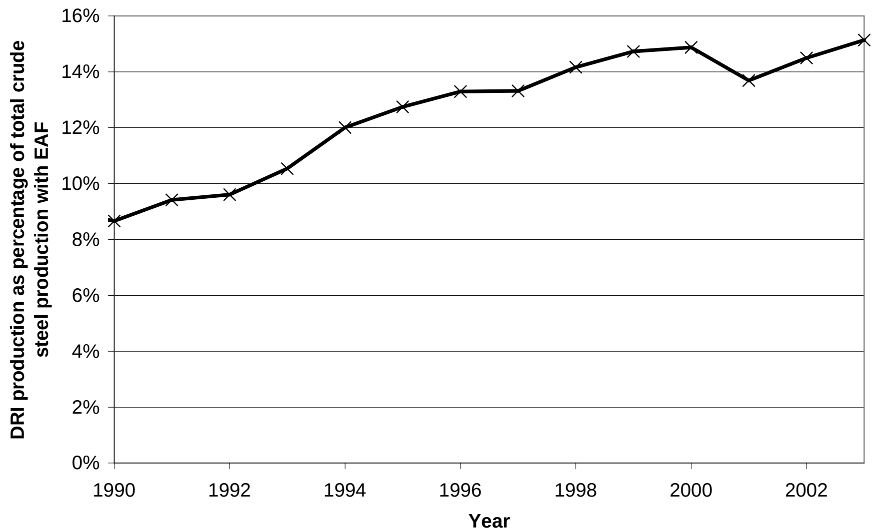


Figure 4-13 Worldwide direct reduced iron production as percentage of crude steel production with electric arc furnaces, 1990-2003.

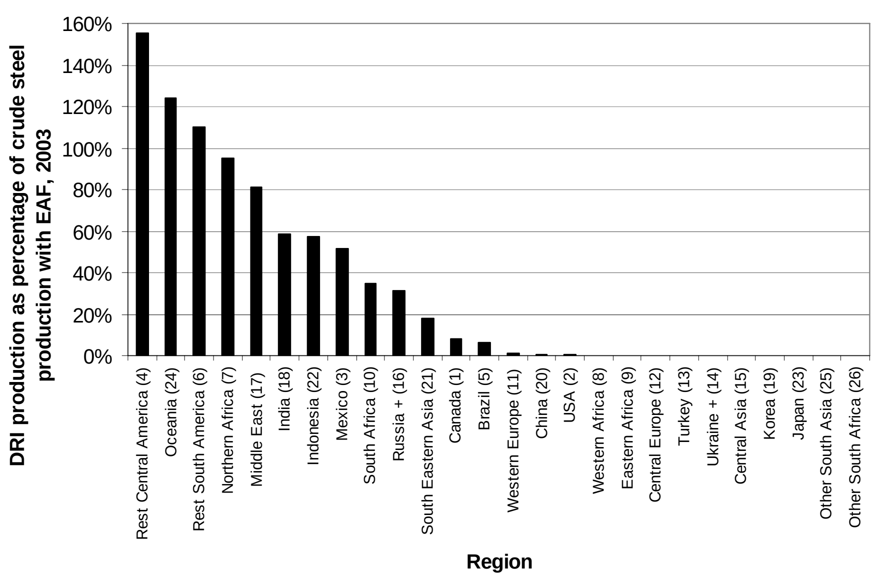


Figure 4-14 Production of Direct Reduced Iron as percentage of crude steel production with electric arc furnaces in 2003.

The overview shows that the share of direct reduced iron in electric arc furnace steel production is gradually increasing and is now at the level of 15%. The percentages shown in Figure 4-14 are not identical to the share of direct reduced iron consumption in electric arc steel production, because direct reduced iron is also traded[15]. In Oceania, for example, direct reduced iron is produced in an export-oriented DRI/HBI plant in Port Hedland, Australia (Steel-technology.com, 2005). It can still be concluded, however, that in some regions of the world (Central and South America, Northern Africa, Middle East, India and Indonesia) electric arc furnaces are to a very large extent operated with primary iron inputs. In some of these regions, direct reduced iron is the main form of primary iron produced (Figure 4-15).

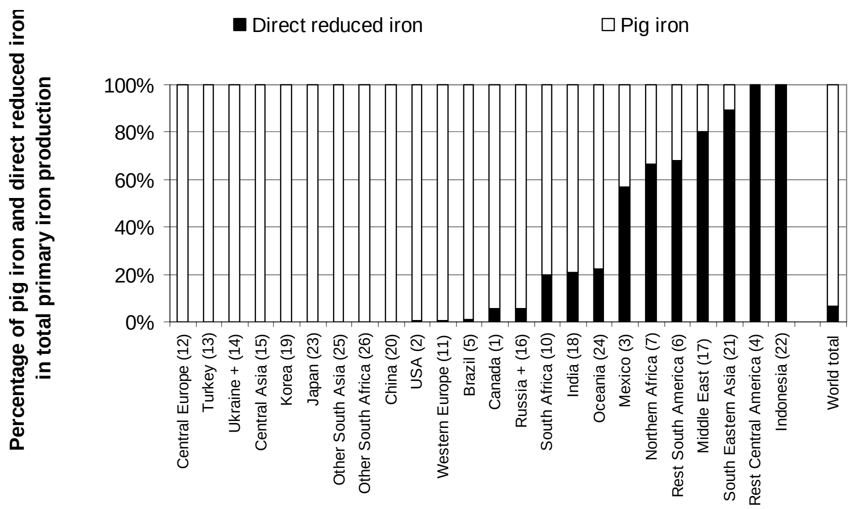


Figure 4-15 Percentages of pig iron and direct reduced iron in total primary iron production in 2003

4.3.5 Availability and recovery of circulating scrap

We define the circulating scrap ratio as the ratio of the circulating scrap production and the crude steel production (F14 / F13 in Figure 4-2). Historically, the circulating scrap ratio has been going down as a result of the introduction of continuous instead of ingot casting. The formula used by the International Iron and Steel Institute to calculate finished steel back to crude steel equivalents (Equation 3-15) can also be used to derive the circulating scrap ratio based on the fraction of continuous cast steel.

A continuous casting ratio of 0% (i.e. 100% ingot casting) translates to a circulating scrap ratio of 23% (1-1/1.3, Equation 3-15) and a ratio of 100% translates into a circulating scrap ratio of 10% (1-1.175/1.3, Equation 3-15). Based on IISI data for the continuous casting ratio (IISI, various years) and Equation 3-15, we calculated the circulating scrap for the various TIMER regions shown in Figure 4-16.

[15] Detailed data on direct reduced iron trade is, however, not available.

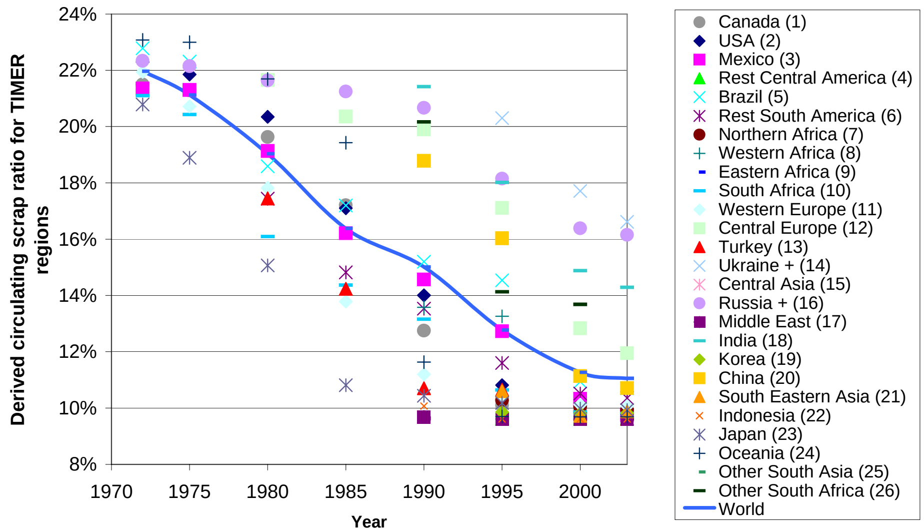


Figure 4-16 Circulating scrap ratio in the various regions and worldwide average

The data shown in Figure 4-16 are confirmed by other sources. Wienert (1996b) uses values of 1.35 tonne crude steel per tonne of finished steel for ingot casting and 1.10 tonne crude steel per tonne of finished steel for continuous casting, equivalent to a circulating scrap ratio of 26% and 9% respectively. In Michaelis and Jackson (2000), the ratio of circulating scrap and finished steel production for the UK is shown to have dropped from over 30% (1954) to approximately 10% (1994), equivalent to a circulating scrap ratio of 23% (1954) and 9% (1994). In the balances made by World Steel Dynamics (WSD, 2005), the circulating scrap availability is directly calculated by subtracting the deliveries of finished and semi-finished steel products from the crude steel production. From their data, a circulating scrap ratio of 32% can be derived for 1975 and a ratio of 12% in 2002 for the US, which is slightly above the ratios calculated with Equation 3-15. Of the circulating scrap, 90% is assumed to be recovered. More historical estimates for the circulating scrap ratio are difficult to find. According to the US Geological Survey mineral yearbook of 1939 (USGS, 1939a,b), in 1937 and 1938, steel furnaces used 13.6 and 7.7 Mt of home (circulating) scrap respectively on a crude steel production of 45.9 and 25.7 Mt respectively. This would correspond to a circulating scrap ratio of approximately 30% in those days if we assume all circulating scrap to be recovered.

It should be noted that circulating scrap is ‘produced’ in the conversion of crude steel to finished steel. Since steel slabs (crude steel) are also already traded, the circulating scrap availability is not necessarily correlated with the crude steel production of a country and is also dependant on the kind of semi-finished and finished steel products made in a country.

4.3.6 Availability and recovery of prompt scrap

Prompt scrap is generated when steel products are made from finished steel. The amount of prompt scrap can therefore be expresses relative to the finished steel consumption (F18 / F17 in Figure 4-2) and via the circulating scrap ratio also relative to the crude steel consumption. In Lardinois (1994, pp. 69), the amount of prompt scrap is estimated at 15% of crude steel consumption, which would correspond to a prompt scrap ratio (as ratio of finished steel consumption) of 0.17 (circulating scrap ratio of 0.1) or 0.19 (circulating scrap ratio of 0.2). In a UN publication (UN, 1995), the amount of prompt scrap is estimated to vary between 8% and 20% of the apparent crude steel consumption. With a circulating scrap ratio of 0.1, this

corresponds to a prompt scrap ratio of 9% - 22%. With a circulating scrap ratio of 0.2, this corresponds with a prompt scrap ratio of 10% - 25%. In Michaelis and Jackson (2000), a prompt scrap ratio of 15% is assumed. Wienert (1996b), report a drop in prompt scrap ratio from 20% in the fifties to 10% in 1993.

In the balances made by World Steel Dynamics (WSD, 2005), a prompt scrap ratio for the US of 20% in 1975 and 13% in 2003 (steel) and 15% in 1975 and 14% in 2003 (foundries) is used. The prompt scrap ratio is very product specific and therefore very much depends on the product mix made from steel. Dahlstrom et al. (2004) gives prompt scrap rates for the 10 sectors distinguished in their study based on a personal communication. For all sectors a prompt scrap ratio of 10% is used, except for the structural steelwork and building and civil engineering sector (5%) and the cans and metal boxes sector (17%). In a United Nation publication (1979), prompt scrap rates for 25 steel consuming sectors are given, ranging from 0% (railway tracks) to 46.7% (precision engineering). An overall-rate of 15.6% is given for 1972.

4.3.7 Availability and recovery of obsolete scrap

In contrast to circulating and prompt scrap, obsolete scrap does not depend on the *production* of steel and / or metal containing products, but on the *consumption* of metal-containing commodities in the past and the lifetime of these products. In order to calculate and project the amount of obsolete scrap available in a region, one needs to know exactly:

- The product mix made from steel
- The lifetime of these products
- The trade in steel containing commodities both at the end and at the beginning of their lifetime
- The dissipation of steel products into the environment

All four elements are region-, product- and time dependant. The amount of steel embodied in products that go to the stock of products in use can be estimated as the apparent crude steel consumption of a country, corrected for the fraction of crude steel that is converted to scrap before it is embodied in final products. A circulating scrap ratio of 42% and a prompt scrap ratio of 30% (1900 assumptions in our model, see Section 4.4.4), implies that only 41% of crude steel consumption is embodied in final consumer products. A circulating scrap ratio of 10% and a prompt scrap ratio of 15% (current situation) implies that 77% of crude steel consumption is embodied in final consumer products. A circulating and prompt scrap ratio of 5% (2100 assumptions in our model, see Section 4.4.4) implies that 90% of crude steel consumption is embodied in final consumer products.

Information on the mix of products made from steel is not easily available. Historical data (1995-2005) for the EU are given in Figure 4-17, based on Eurofer data (Eurofer, 2005). The figure shows that the percentages have not significantly changed in the last 10 years. This is also confirmed in a study by Dahlstrom et al. (2004), which gives data for the UK for the period 1975-2000 (Figure 3.2 in her study). For the US, historical data are shown in Figure 4-18 (USGS, various years). The data are difficult to interpret, because the categories ‘others’ and ‘service centres and distributors’ take a large part of the consumption and it is unclear what is included in these categories. In recent years, the share of containers in total steel consumption seems to have decreased at the expense of construction steel, but the unclear sector classification and the occurrence of some unexplainable yearly variations (e.g. in machinery) makes it difficult to distinguish clear trends. For Japan in 2003, the share of buildings and public works in total steel consumption was 45%, the share of cars was 21%, machinery 22%, packaging 3% and the category of Secondary Products 9% (IISI, 2005b). In an Indian source (Banerjee, 2004), it is shown that the construction sector has a considerably

higher market share in China (54%) compared to India (35%), but it unclear which sectoral classification is used.

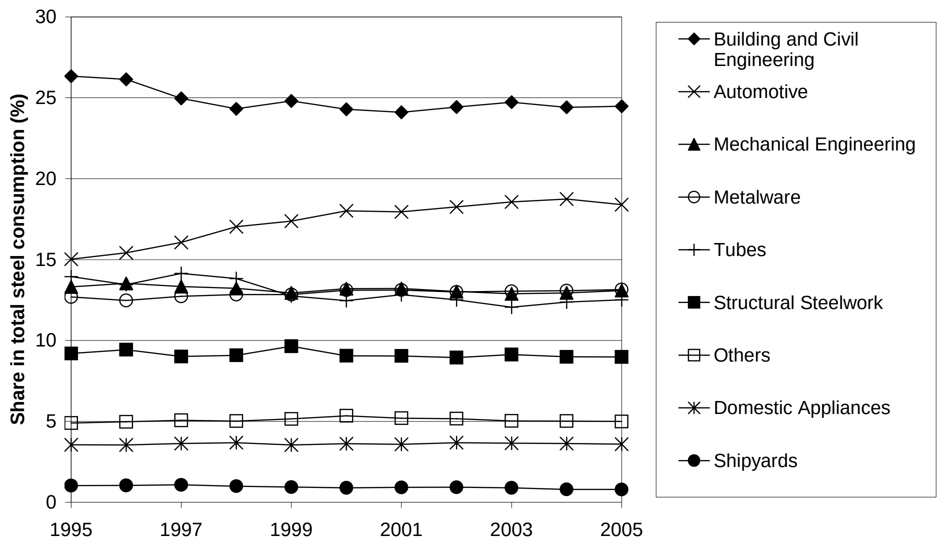


Figure 4-17 **Sectoral weights (%) in total steel consumption in the EU, 1995-2005 (Eurofer, 2005)**

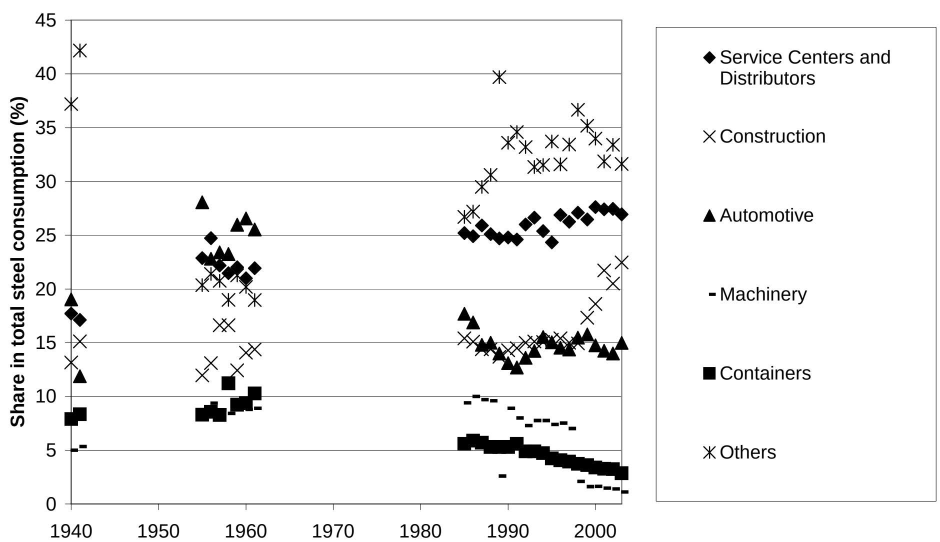


Figure 4-18 **Sectoral weights (%) in total steel consumption in the US, 1940-2003 (USGS, various years)**

In literature, a number of studies can be found that try to calculate obsolete scrap recovery rates based on the average lifetime of steel products and historical steel consumption figures. Michaelis and Jackson (2000) calculate a weighted average lifetime of 14 years, based on an analysis for 10 types of products. The lifetime assumptions for some of the products (e.g. motor vehicles 7 years and construction 30 years) seem to be on the low side. Using this lifetime, a post-use recycling rate between 74 and 41% is calculated for the period 1969 – 1994 in the UK. In this study, all trade flows are taken into account, including indirect trade in steel-containing commodities. The authors point out that the 'few data points and the

assumptions necessary for this estimate mean that this inference should be treated with caution'.

In a study by Dahlstrom et al. (2004), an inferred recycling rate is calculated for the UK in 2001 based on the lifetime assumptions given in Table 4-4 and using three types of lifetime distributions (no distribution, log-normal distribution and Weibull distribution). The inferred recycling rate calculated using these distributions is 69-72%. These recycling rates include also prompt scrap. If prompt scrap is excluded from the calculation, the obsolete scrap recovery rate is 68% (based on Figure 3-25 from the report, (3501+4818-171-1383)/(10013)). Using the same assumptions for the lifetime of steel products, Moll et al. (2005), estimate the total amount of 'end-of-life' goods to be available in the EU15 in 2000 to be 86.5 Mt (Figure 30 in their report). Based on these estimates, an obsolete scrap recovery rate of 66% can be derived from their figures for the EU15.

Table 4-4 Lifetime of steel products given by Dahlstrom et al. (2004)

Sector	Lifetime (range)
Mechanical engineering	15 (10-20)
Electrical engineering	16 (10-25)
Shipbuilding	60
Vehicles	13 (11-16)
Structural steelwork and building and civil engineering	60 (20-100)
Metal goods	13 (5-15)
Cans and metal boxes	1
Boilers drums and other vessels	10
Other industries	25

In Lardinois (1994), a list is given of products with certain assumed lifetimes and the recycling ratio. Unfortunately, no source is given for the figures. Based on an assumed average lifetime of approximately 15 year (which seems not to be derived from the table, but exogenously assumed), a recycling rate of 33% is calculated using the ratio of past consumption and current use of obsolete scrap.

Table 4-5 Lifetime of steel products given by Lardinois (1994)

	Lifetime	Recycling ratio
Cans	2	50%
Cars	12	90%
Machines	20	90%
Steel furniture	22	60%
Shipbuilding	26	80%
Locomotives	32	95%
Construction steel	32	80%
Bridges	50-100	40%

Fenton (2005) assumes an average lifetime of 19 years based on the data given in

Table 4-6. Based on this data, he derives an obsolete scrap availability for the US of 75 Mt in 1998. This is based on the shipments of steel products, excluding indirect trade. The actual obsolete scrap consumed in 1998 was 35 Mt in 1998 and the net export of scrap was 3 Mt, resulting in an obsolete scrap recovery rate of (35+3)/75 = 51% for 1998 (Fenton, 2004).

Table 4-6 Lifetime of steel products assumed by Fenton (2005).

Steel consuming industry	Lifetime of steel product
Steel for converting and processing	19
Independent forgers (not elsewhere classified)	19
Industrial fasteners	19
Steel Service Centres and Distributors	19
Construction, including maintenance	30
Contractors' products	30
Automotive	10
Rail transportation	30
Shipbuilding and marine equipment	30
Aircraft and aerospace	20
Oil, gas and petrochemical	30
Mining, quarrying and lumbering	15
Agricultural	20
Machinery, industrial equipment and tools	15
Electrical equipment	20
Appliances utensils and cutlery	10
Other domestic and commercial equipment	10
Containers, packaging and shipping materials	1
Ordnance and other military	15
Non-classified shipments	19

In Wienert (1996a), based on very simple regression analysis (shifting the steel consumption to obtain the best fit with the obsolete scrap use), a recycling rate of 33% is calculated, based on an average lifetime of 9 years. Birat and Zaoui (2002) mention collection rates of 95% for automobiles, 48% for packaging, 68% for buildings and bridges and 65% for home appliances in the EU-12 in 1995. In the same source, the total collection rate of obsolete scrap is given for the EU-12 countries for the period 1950-2020. The collection rate went down from almost 90% in 1950 to 65% in 1990 after which the collection rate started to increase again to approximately 70% in 2000. Unfortunately, the methodology applied to come to these estimates is not explained. In other sources, Birat (Unknown year, pp. 5 and 2000, pp. 1353) mentions collection rates between 70-85%. In a publication by the American Steel Recycling Institute (2003), an overall obsolete steel recycling rate of 83% is given. Individual rates are given for municipal waste (32%), containers (60%), automotive (95%), other durables (95%) and construction (85%). It is not fully clear, which methodology is applied in determining these figures, because a recycling rate of 45% is mentioned for reinforcement bars in a study by the American Iron and Steel Institute (AISI, 2001), quoting the same Steel Recycling Institute.

To summarize, we can conclude that quite wide ranges are found in open literature for the average lifetime of steel products and for the recycling rate of obsolete scrap.

4.3.8 Scrap trade

According to Mackrall (2004), 81 Mt of merchant scrap was traded internationally. A similar figure for international merchant scrap export in 2003 (78 Mt) is found in the Steel Statistical Yearbook (2004). These figures include intraregional trade. We derived the net interregional trade in scrap for 2003 and summarise it in Table 4-7. The time series of net export for some important regions are shown in Figure 4-19. Some doubts about the quality of the data are justified since net export and net imports differ by 2.5 Mt, but a general pattern can still be deducted from the table. Developed regions (including the regions of the former communist

regions) are net exporters of scrap with the exception of Western Europe, whereas developing and less developed countries are net importers of scrap.

Table 4-7 Net intraregional scrap trade in 2003 in the TIMER regions

Net exporters		Net importers	
Region	**Quantity (Mt)**	**Region**	**Quantity (Mt)**
Russia (16)	7.7	China	11.6
USA (2)	7.5	Turkey	11.0
Central Europe	6.5	Korea	5.8
Japan (17)	5.5	Western Europe	2.6
Others	8.0	Others	6.5
Total	35.2	Total	37.5

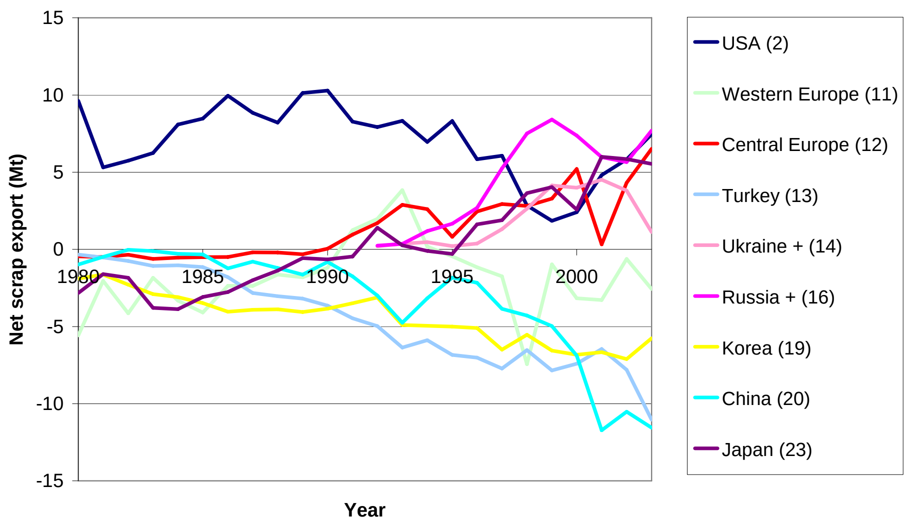


Figure 4-19 Net steel scrap export for regions having a net export of +/- 5 Mt in any of the years shown. Ukraine and Russia only shown from 1992 onwards.

4.4 Detailed model description and exogenous model parameters

4.4.1 Production and trade of steel

For the period 1900-1970, steel trade is totally neglected and apparent crude steel consumption is set equal to historical crude steel production. For the period 1970-2003, historical data on steel production and consumption is used and net steel export is derived by deducting consumption from production levels. For the projections, steel trade and resulting steel production are not endogenously modelled. Instead, we determine trade by means of exogenous model assumptions. We distinguish three cases. In the default case:

1. Absolute trade flows is frozen to 2003 levels.

This assumption has the advantage that trade flows are automatically balanced (net export = net import) and results in the following trade developments over time:

- Regions with stable projected apparent crude steel consumption levels compared to 2003 levels also have stable relative trade flows in this trade assumption. This in

general holds for the developed regions of the world (saturated per capita steel consumption combined with stable or slightly decreasing population).

- Regions with increasing apparent crude steel consumption levels compared to 2003 levels have decreasing relative trade flows in this trade assumption. This holds for most developing regions (increasing per capita steel consumption, often combined with increasing population). This assumption therefore 'automatically' results in a declining relative net import when a country develops which is in line with the trade pattern for developing countries assumed by Wienert (1996a) and discussed in Section 4.1.2. However, in this trade scenario, currently importing regions remain net importers. The shift from being a net importer to being a net exporter (sometimes followed by a switch back to being a net importer) as discussed in Section 4.1.2 is not simulated by this trade scenario.
- Regions with decreasing apparent crude steel consumption levels compared to 2003 have increasing relative trade flows in this assumption. This is for example the case for developed regions with stabilising or declining per capita apparent crude steel consumption and / or declining population.

In the model, two alternative assumptions regarding trade are also included. As part of the sensitivity analysis (Section 7.5), we will show results using these alternative trade assumptions:

2. No steel trade; steel consumption equals steel production
3. Region-specific relative steel trade

Using the second assumption, trade is totally neglected. All regions are assumed to have a crude steel production equal to the apparent crude steel consumption. Analysis of historical data (Figure 4-4, Figure 4-5, Table 4-1) reveals that, especially for less developed regions significant errors are made using this zero trade assumption. However, the error made is relatively small (< +/- 20%) for the more developed regions of the world (Canada, USA, Western Europe, Korea) having income levels above 10,000 1995 ppp $ per capita. The only exception is Japan having net export of 43% in 2003 (Table 4-1).

In third trade assumption, we use a tailored approach with a specific development of the relative trade as function of per capita income and/or time. The approach is partly based on the general trade pattern as function of per capita income as given in Figure 4-1 and discussed in Section 4.1.2:

- Low developed regions (per capita income lower than 10,000 1995 ppp $) currently having a net import of crude steel are assumed to have a decreasing import dependency in the course of their development. The net import is assumed to decline linearly as a function of per capita income and to reach a net import level of 0% at a per capita income level of 10,000 1995 ppp $. At higher income levels, the net import is kept at 0%. This method is used for Region 3 (Mexico), 4 (Other Central America), 6 (Other South America), 7 (Northern Africa), 8 (Western Africa), 9 (Eastern Africa), 17 (Middle East), 18 (India), 20 (China), 21 (South Eastern Asia), 22 (Indonesia), 25 (Other South Asia) and 26 (Other South Africa).
- The net export of the former centrally planned economies 12,14,15 and 16 (Central Europe, Ukraine +, Central Asia and Russia +) is assumed to result mainly from the declining apparent crude steel consumption figures after the collapse of the communist governments, resulting in large overcapacities and a net export tendency. For those regions, the current production level is lowered by 3% per year (to simulate shutdown of part of the current capacity) until the net export reaches a level of 0%. After this point, a net export of 0% is maintained.

- For the other regions with a per capita income level above 20,000 1995 ppp $ and for the regions that have already reached a level in which they became net steel exporters (Brazil, South Africa, Turkey and Korea), in principle the relative net export levels of 2003 are maintained (Table 4-1). To balance the overall trade (net total exports should be 0), we arbitrarily chose to change the relative net export percentage[16] of the exporting regions (Western Europe, Japan, Brazil and South Africa), while keeping the relative percentage of the importing regions constant.

We would like to emphasise that none of the three trade assumptions is based on any sound and consistent economic or other theory. In the final chapter of this report, we discuss possibilities to endogenously include steel trade in the model.

4.4.2 Steel production by technology

In this study, we attempt to give very long-term scenario projections. To assess the energy use and CO_2 emissions from steel production, the most critical parameter to project is the amount of steel produced from primary resources (iron ore) versus the amount of steel produced from secondary resources (scrap). One possibility for estimating the share of secondary resources in steel production is to project the share of electric arc furnaces in the total steel production and to assume electric arc furnaces to be equivalent to secondary steel production. Given the fact that the iron sources for electric arc furnaces have become increasingly diversified (Chapter 2) and given the fact that scrap is also used in basic oxygen furnaces and open-hearth furnaces, this might lead to misleading results for some regions (Figure 4-14). In our projections, we do therefore not only distinguish between primary and secondary production, but we distinguish between three steel production routes with fixed percentages of secondary iron (scrap) and primary iron inputs, complemented with the production of iron foundries.

Table 4-8 Percentage of scrap and primary iron in three production routes

Route	Scrap percentage in input	Primary iron percentage in input
Pig iron – BOF – Route 1	10	90
DRI – EAF – Route 2	0	100
Scrap – EAF – Route 3	100	0
Foundries	100	0

With the material flow analysis (Section 4.4.3 – Section 4.4.6), we project the amount of available scrap resulting from current steel production and past steel consumption levels, taking into account recovery ratios for the various scrap types (Figure 4-2). We assume this scrap to be fully used in steel production. The remaining part of the total iron requirement (Section 4.4.3) has to be covered by primary iron resources. The shares of the various routes are deducted from the total scrap requirements:

$$\begin{aligned}&\textit{Total scrap consumption} = \\&\sum_{i=1}^{3}(\textit{share route}_i * \textit{specific iron requirements}_i * \textit{scrap percentage input}_i * \textit{steel production}\ ) \\&+ \textit{production iron foundries} * \textit{specific iron requirements}_{\textit{foundries}} * \textit{scrap percentage in input}\end{aligned}$$

Equation 4-1

[16] If for example a net export of 40 Mt is projected for Western Europe, Japan, Brazil and South Africa) using the constant percentages for 2003, but only a net export of 20 Mt is required to balance trade resulting from the assumptions made for the other regions, we multiplied the percentages for 2003 for the four regions with a factor 0.5.

In this equation, the total scrap consumption (Section 4.4.7), the production in iron foundries, (Section 3.4.2) the specific iron requirements of the steel production route (Section 4.4.3), the scrap percentages in the input (Table 4-8) and the steel production are all known, leaving the shares of the three routes as three independent variable. Fixing the share of one the three routes is sufficient to calculate the remaining two shares[17]. In our projections, we use the share of direct reduced iron in total primary iron production (Figure 4-15) as the exogenous variable to determine the share of route 2. We use the shares of direct reduced iron in total primary iron production in 2003 given in Figure 4-15 for all years until 2100.

4.4.3 Specific iron requirements per tonne of crude steel

We base our assumptions for the specific iron requirement per tonne of crude steel on the data provided by World Steel Dynamics (WSD, 2005) given in Table 4-2 for 1975-2003 and corrected for the fact that pig iron only contains 96% iron. For 1900, we assume, a specific iron requirement of 1.25 for all routes and for 2100 we use a ratio of 1.05 for all routes. In intermediate years, we use linear interpolation. Data availability is insufficient to distinguish between the various regions.

Table 4-9 Specific iron requirements per tonne of crude steel (tonne / tonne)

Year	OHF[1]	BOF (route 1)	EAF (route 2/3)
1900[2]	-	1.25	-
1975[3]	1.20	1.17	1.16
2003[4]	1.19	1.13	1.09
2100	-	1.05	1.05

[1] For the historical data until 2003, we separately include open-hearth furnaces. From 2003, onwards, open-hearth furnaces (expected to disappear in the coming decade) are included in the basic oxygen furnace route.

[2] Before 1979, we assume all steel to be produced via the basic oxygen furnace route (Section 4.4.2).

[3] Based on Table 4-2, assuming 100% ingot casting. For OHF and BOF, multiplied with 0.96 to correct for iron content of pig iron (main input).

[3] Based on Table 4-2, assuming 100% continuous casting. For OHF and BOF, multiplied with 0.96 to correct for iron content of pig iron (main input).

In line with the assumptions made by World Steel Dynamics, we assume no recovery of the iron input not embodied in the crude steel. For iron foundries, we use a specific iron input of 1.50 tonne iron / tonne of cast iron input. We assume the excess iron to be fully recovered as circulating scrap.

4.4.4 Circulating scrap

We use the estimates from Figure 4-16 for the circulating scrap ratio for 1972 – 2003. For 1960, when continuous casting was first introduced, a circulating scrap ratio of 0.23 is assumed for all regions. For 1938, a ratio of 0.3 is assumed for all regions (based on the US, see Section 4.3.5). For 1900, the development between 1938 and 1960 was extrapolated linearly yielding a ratio of 0.42 in 1900. The assumption was made that in 2010, all countries will have introduced continuous casting to nearly 100%, resulting in a circulating scrap ratio of 0.10. Between 2010 and 2100, further improvement to a ratio of 0.05 is assumed. In intermediate years, we use linear interpolations. We assume all circulating scrap to be recovered.

[17] Since the sum of the three shares has to be equal to 1, fixing the share of one of the variables yields a set of two equations with two unknown variables.

4.4.5 Prompt scrap

Based on the data from World Steel Dynamics (WSD, 2005) given in Section 4.3.6, we use a prompt scrap ratio of 0.20 in 1975 and 0.13 in 2000. For the future, we assume further improvement to ratio of 0.05 in 2100. For the past, we assume a prompt scrap ratio of 0.30 in 1900. Data is insufficient to make the prompt scrap ratio region specific. We assume all obsolete scrap to be recovered.

4.4.6 Obsolete scrap

We distinguish four product categories in the model, corresponding with steel used for products having different economic lifetimes (based on Mueller, 2005). The products become available as obsolete scrap in years following their production according to a certain lifetime distribution. We assume normal lifetime distributions and a fixed percentage of steel going to the various product categories based on the data presented in Section 4.3.7. A summary is provided in Table 4-10, a graphical representation of the used lifetime distribution in Figure 4-20.

Table 4-10 Overview product groups

Group	1	2	3	4
Representative for:	Construction	Machinery	Cars	Cans
Share in steel production (%)	35	25	25	15
Average lifetime	70	20	15	5
Standard deviation	30	7	5	3

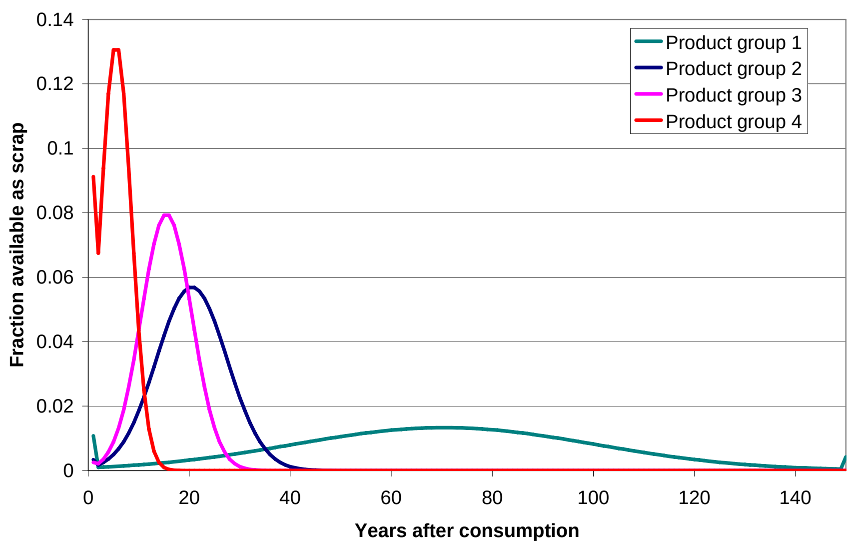


Figure 4-20 Lifetime distribution assumed for four product categories

4.4.7 Historical fraction of secondary steel and obsolete scrap recovery rate

Based on the historical production of steel, the historical production and trade of primary iron and the assumptions on specific iron requirements (Section 4.4.3), circulating scrap availability (Section 4.4.4) and prompt scrap availability (Section 4.4.5), we can estimate the historical amount of obsolete scrap required to close the balance of metallics required for the production of steel. This amount of obsolete scrap can be coupled with the amount of obsolete scrap available, estimated based on historical steel consumption per product and the assumed lifetime distribution (Section 4.4.6). The historical obsolete scrap recovery rate is calculated using the following formula:

obsolete scrap recovery rate =

(obsolete scrap required + scrap export – scrap import) / (steel coming out of use)

Equation 4-2

The amount of total scrap required is based on the total metallics required for the production of crude steel, corrected for the amount of primary iron available:

total scrap required =

iron required foundries + iron required steel production – primary iron production + primary iron export – primary iron import

Equation 4-3

The total amount of obsolete scrap required is calculated by deducting the circulating and prompt scrap available from the total scrap requirements:

obsolete scrap required =

total scrap required – circulating scrap available – prompt scrap available

Equation 4-4

The historical fraction of secondary inputs in the total iron requirements is calculated using the following equation:

fraction of scrap in total iron requirements =

total scrap required / (iron required foundries + iron required steel production)

Equation 4-5

The historical results of this calculation will be shown in Chapter 6. Based on the historical analysis, we assume an exogenous obsolete scrap recovery rate for the future. Using this recovery rate, we project the total amount of scrap available using the following formula:

total scrap available = circulating + prompt + obsolete scrap

Equation 4-6

The total scrap available is then used to calculate the shares of the three technologies in the total steel production as explained in detail in Section 4.4.2.

4.4.8 Scrap trade

Given the relatively minor importance of scrap trade relative to total scrap consumption (trade of 35 Mt on a total scrap consumption of approximately 500 Mt, see Section 4.3.8 and 6.1), we neglect scrap trade in our projections.

4.4.9 Calculations of stocks

As indicated in Figure 4-2, we also calculate cumulative iron losses during steelmaking (*C10 Iron loss-1*), cumulative losses from the incomplete recovery of circulating and prompt scrap (*C11 Iron loss-2 and C12 Iron loss-3*), cumulative iron losses from the incomplete recovery of obsolete scrap (*C13 Iron loss-4*) and the total stock of iron in use (*C8, Steel containing end-products in use*). To close the overall mass balance of the system, the total iron losses from the system and the total stock of iron in use should be balanced by the total flow of primary iron into the system (*C4, Primary iron*). Since we assume 100% recovery of circulating and prompt scrap (Section 4.4.4 and 4.4.5), cumulative losses from the incomplete recovery of circulating and prompt scrap remain 0. Cumulative iron losses from the conversion from iron to steel are calculated by summing the yearly losses calculated with the following formula:

iron losses during steelmaking =

*(iron required steel production – crude steel production) * (1- iron to steel recovery ratio for steel) + (iron required foundries – foundry production)*(1- iron to steel recovery ratio for foundries).*

Equation 4-7

The assumptions for the iron to steel recovery ratio are described in Section 4.4.3. The total stock of iron products in use is calculated by summing the yearly change of stock of products in use calculated with the following formula:

change in stock of products in use = (products going to use – products coming out of use)

Equation 4-8

We assume the total stock in use in the initial year 1900 to be the apparent crude steel consumption in 1900 (= equal to crude steel production in 1900 in our model) per product category, multiplied with the average lifetime assumed for the product category. This implicitly assumes the crude steel production to be equal to the 1900 production during the average lifetime of these products. For construction steel (product group 1), this would lead to unrealistically high initial stocks in 1900. Therefore, we multiplied the apparent crude steel consumption in 1900 for product group 1 with 20 instead of 70 to avoid overestimation of the stock. The initial stock in 1900 is assumed to become available as obsolete scrap in (1 / average lifetime) equal steps after 1900.

The yearly non-recovered obsolete scrap are historically calculated by deducting the obsolete scrap required from the total of products coming out of use in that year:

non-recovered obsolete scrap = total products coming out of use – obsolete scrap required

Equation 4-9

The formula used to calculate the total amount of obsolete scrap required is given in Equation 4-4. In the projections where we use an exogenous obsolete scrap recovery rate, the losses from incomplete recovery of obsolete scrap are calculated using the following formula:

*losses from incomplete recovery of obsolete scrap = (1-obsolete scrap recovery rate) * (total products coming out of use)*

Equation 4-10

5 Energy use and CO_2 emissions

5.1 Modelling approaches, overview of existing models

In projecting future energy use, CO_2 emissions and energy costs related to steel production, two paths can be taken:

1. Exogenous assumptions for the development of the specific energy consumption
2. Endogenous modelling of specific energy consumption as function of e.g. the cumulative production, energy prices etc.

Of the models given in Appendix 2, Hidalgo et al. (2003), uses exogenously fixed declining specific energy consumption data. Except for certain technology-specific fuel uses (e.g. cokes in blast furnace and the electricity demand), fuels can substitute each other, driven by differences in fuel costs. These fuels choice is influenced by emission costs that can be set via various carbon price scenarios. The fuel choice also influences the total production costs of steel via various technologies, thereby also influencing the choice of production route in the model. Das and Kandpal (1998) also uses fixed specific energy consumption values as well as Gielen and Moriguchi (2002), Gielen and van Dril (1999) and Michaelis and Jackson (2000). Comparable to the IPTS model, the influence of energy and emission costs on trade and technology choices are endogenously included in the models by Gielen. In the VLEEM work (2005), exogenous assumptions on energy consumption values are used until 2050 based on information from literature and for the remaining period (until 2100) based on extrapolation of the 2000-2050 trend, taking into account the thermodynamic minimum energy requirements for certain routes.

In the metals model developed by van Vuuren et al. (1999), the specific energy use for mining and milling is dependant on ore grade decline (i.e. the specific energy use for mining ore) and on the cumulative production via a technological learning curve, taking into account the thermodynamic minimum energy requirements using the following formula:

$$SEC_i = (SEC_{min}) / g + (SEC_{i,0} * CP^b) / g$$

Equation 5-1

With SEC_i the specific energy consumption to produce steel, SEC_{min} the thermodynamically minimum energy requirement, $SEC_{i,0}$ the specific energy consumption of the first unit produced, CP the cumulative production of primary or secondary steel and b the experience index.. With this formula, one assumes the specific energy consumption to go down with a fixed percentage each time the cumulative production doubles. The factor g is a factor that is determined by the ore grade decline (over time, the factor g goes down and specific energy use increases as a result). In the calibration of their model, van Vuuren et al. found that for iron and steel, ore grade decline is relatively unimportant. For the specific energy use for smelting and refining, van Vuuren et al. (1999) use the same formula, but in that case without the ore decline factor.

Ruth (1998) models energy use as function of either production rates or cumulative production. In the model by Hidalgo et al. (2003), regional differences in specific energy consumption are included, although the publications are not very specific about the method used to distinguish between regions. The same holds for the publications by Gielen and Moriguchi (2002) and Gielen van Dril (1999). The VLEEM model (2005) distinguishes

between industrialized and developing countries. The gap in specific energy consumption between industrialized versus developing countries is expected to decrease to 8% for primary steel and 19% for secondary steel compared to the level for industrialized countries in 2100.

An interesting body of work with respect to energy efficiency differences between countries and possible convergence of these efficiency levels in the coming decades are studies dealing with future commitments under the climate conventions (e.g. the theses by Phylipsen, 2000, Groenenberg, 2002 and Höhne, 2005 and publications by Phylipsen et al., 2004 and den Elzen and Lucas, 2003 on the tryptich approach). In the various versions of the triptych model, either fixed energy efficiency improvements over time are applied to all regions (e.g. 1.5% per year) or global convergence to a certain exogenously assumed energy efficiency level in a certain year. For both, energy (or carbon) efficiency levels in a certain base year should be known. In Section 5.3, we will present quantitative information on regional energy efficiency levels used in these studies.

5.2 General description of modelling approach

In our model, we included a simple capital vintage model that calculates for each year the required capacity for each of the three production routes distinguished. The calculation routine of the model can be summarised as follows:

For each year, the required capacity for each of the three production routes is calculated based on the amount of available scrap (Section 4.4.2, Equation 4-1).

- New capacity is calculated by comparing with the capacity of the previous year, taking into account depreciation of old capacity.
- Old capacity is depreciated in 21 equal steps between the 20 and 40 years after installation.
- New capacity is given a certain specific energy consumption, which is maintained during the entire lifetime of the capacity.

An attempt was made to construct a specific energy consumption curve based on the learning curve concept and historical specific energy consumption figures, but this did not result in directly usable results and is left as an exercise for future study. Instead, we use the following formula:

$$SEC_{region, technology, fuel\ type} = SEC_{reference, technology, fuel\ type} * EEI_{region, technology, fuel\ type, year}$$

Equation 5-2

The $SEC_{region,\ technology,\ fuel\ type}$ is the specific energy consumption in a certain region for a certain technology and fuel type. The $SEC_{reference,\ technology,\ fuel\ type}$ is a reference specific energy consumption per technology and fuel type and the $EEI_{region,\ technology,\ fuel\ type,\ year}$ is an energy efficiency indicator giving the relative energy efficiency compared to the reference level. We distinguish between two fuel types (fuel and electricity use). Combined with exogenous assumptions on the types of fuels used and the specific CO_2 emission factors of these fuels, total CO_2 emissions are calculated. CO_2 capture and storage is not included as such in the model, but will receive attention in the final chapter of this report.

5.3 Overview of past trends and parameters based on past trends

As stated already in Section 2.3, specific energy use data can be found in a large number of literature sources and can also be derived by combining international energy statistics with steel production data. However, system boundaries are not always straightforward and consistent between literature sources and allocation of energy use to the various individual

process units is by no means straightforward. The ranges presented by Price et al. (2002) which are given in Table 2-3 give an indication of the observed specific energy consumption levels and are also confirmed by other literature sources such as Daniels (2002).

In Table 5-1, we present estimates for current and future average worldwide specific energy consumption figures for various technologies in 2000 and 2030 as used by Hidalgo et al. (2003) and in Table 5-2, we give the values used in the VLEEM study (2005).

Table 5-1 Average world primary energy consumption per tonne of crude steel in 2000 and 2030 for various steel production routes (deducted from graph in Hidalgo et al., 2003).

Process	**SEC, 2000 (GJ/t)**	**SEC, 2030 (GJ/t)**
BOF	31	25
Advanced BOF[1]	18	17
EAF	15	12
Advanced EAF[1]	8	7
DRI	22	18
SR	25	21

[1] Advanced route incorporate all best available technologies

Table 5-2 Primary energy consumption per tonne of crude steel in 2000 and 2100 (VLEEM, 2005)

Process	**SEC, 2000 (GJ/t)**	**SEC, 2100 (GJ/t)**
Primary steel, industrialized countries	16.8	10.6
Primary steel, developing countries	35.3	11.4
Secondary steel, industrialized countries	7.1	3.2
Secondary steel, developing countries	16.5	3.8

For the purpose of our modelling approach, we need both a suitable reference energy use and the relative regional energy efficiency levels compared to this reference level. To our knowledge, the most detailed overview of regional energy efficiency levels for various industries can be found in Groenenberg (2002). For the iron and steel industry, they base energy efficiency levels on best practice levels from Worrell et al. (1997). We present these best practice levels in Table 5-3[18] and the resulting energy efficiency levels in Table 5-4. The findings by Groenenberg confirm other studies with international comparisons such as Price et al. (2002) and Worrell et al. (1997).

Table 5-3 Best practice specific energy consumption levels taken from Worrell et al. (1993 and 1997).

Process	**Fuel (GJ / t)**	**Electricity (GJ_e / t)**	**Primary (GJ / t)[1]**
PI-BOF, slabs	15.86	0.42	16.91
Scrap-EAF, slabs	0.79	1.52	4.59
Hot rolling	1.82	0.37	2.75
Cold rolling	1.10	0.53	2.43

[1] Assuming an efficiency of 40% for electricity generation.

[18] The best practice levels in Worrell et al. (1997) do not include coke production. Since we do want to include coke production in our analysis, we added the specific energy consumption for coke production based on Worrell et al. (1993).

Table 5-4 **Energy efficiency of iron and steel production in 1991 compared to best practice levels (Groenenberg, 2002). Best practice levels given in Table 5-3**

Country	TIMER region	SEC_{actual}	$SEC_{reference}$	EEI steel
United States	2	23.0	13.3	1.7
Mexico	3	22.6	14.2	2.0
Brazil	5	23.2	18.6	1.2
Belgium	11	20.0	17.6	1.1
France	11	24.2	15.8	1.5
Germany	11	18.3	16.5	1.1
Italy	11	17.6	16.0	1.1
Netherlands	11	20.7	18.6	1.1
Portugal	11	16.8	12.7	1.3
United Kingdom	11	22.4	16.2	1.4
Poland	12	28.1	15.3	1.8
India	18	37.4	17.4	2.2
South Korea	19	20.7	15.6	1.3
China	20	36.7	17.8	2.3
Japan	23	21.1	15.6	1.4

Unfortunately, Worrell and Groenenberg did not take direct reduced iron production into account in their analyses. For direct reduced iron production, we use best practice levels for fuel (10.90 GJ) and electricity (0.38 GJ_e) based on a publication by the International Iron and Steel Institute (1998). If we add the specific energy use for the electric arc furnace from Table 5-3 to these values, this results in a specific fuel consumption of 11.7 GJ / tonne and a specific electricity use of 1.9 GJ / tonne for slabs produced via the DRI-EAF process.

5.4 Detailed description of the model

5.4.1 Energy use

To convert the best practice levels given in Section 5.3 for the individual process steps to specific energy consumption figures for the total production of steel, one needs to make an assumption about the share of steel, which is respectively hot and cold rolled. We assume 100% of the crude steel to be hot-rolled and 25% of the crude steel to be both hot- and cold-rolled, rough estimates based on data for the EU from ITPS (2001a,b). The resulting reference specific energy consumption, which we use in our model, is given in Table 5-5.

Table 5-5 **Reference specific energy consumption levels for three production routes**

Process	Fuel (GJ / t)	Electricity (GJ / t)	Primary (GJ / t)
PI-BOF	17.96	0.92	20.26
DRI-EAF	13.79	2.40	19.79
Scrap-EAF	2.89	2.02	7.95

Energy efficiency levels compared to the best practice levels given in Table 5-5 for the TIMER regions in 1990 were based on research by Groenenberg (2002) and are given in Table 5-6. One of the difficulties is that the energy efficiency indicators found in Groenenberg refer to levels of technology in place in 1990, whereas we need specific energy consumption of new installed capacity (see Section 5.2). We assume the energy efficiency levels determined by Groenenberg for 1990 to represent average plants built in 1980 and derive energy efficiency levels based on this assumption. Based on literature data, we project the best practice specific energy consumption level to drop to 0.88 in 2030 (best practice level in 1990 is 1.00). For 2050 and 2100, we extrapolate the development of the best practice level between 1990 and 2030 by assuming similar yearly efficiency improvements. This results in best practice levels of 0.83 in 2050 and 0.70 in 2100 (compared to the level of 1.00 in 1990). We assume convergence of all regions to the best practice level in 2050. Based on these

assumptions, we calculate yearly efficiency improvements from 1980 - 2050 per region using the following formula:

$$yearly\ efficiency\ improvement = 100 * (1 - (EEI_{conv} / EEI_{act})^{(1/t_{conv})})$$

Equation 5-3

With EEI_{cov} = 0.83, EEI_{act} the levels for 1980 and t_{conv} 70 years (i.e. 2050 – 1980). The resulting energy efficiency levels are given in Table 5-6 for 1960-2100.

Table 5-6 Assumed energy efficiency levels for new capacity in the TIMER regions

	1960[3]	1980[4]	1990[3]	2030[5]	2050[6]	2100[7]
Development best practice			1.0	0.88	0.83	0.70
Canada (1)[1]	1.48	1.3	1.22	0.96	0.83	0.70
USA (2)[2]	2.09	1.7	1.53	1.05	0.83	0.70
Mexico (3)[2]	2.58	2.0	1.76	1.11	0.83	0.70
Other Central America (4)[1]	2.58	2.0	1.76	1.11	0.83	0.70
Brazil (5)[2]	1.34	1.2	1.14	0.94	0.83	0.70
Other South America (6)[1]	1.78	1.5	1.38	1.01	0.83	0.70
Northern Africa (7)[1]	1.93	1.6	1.46	1.03	0.83	0.70
Western Africa (8)[1]	1.93	1.6	1.46	1.03	0.83	0.70
Eastern Africa (9)[1]	1.93	1.6	1.46	1.03	0.83	0.70
South Africa (10)[1]	1.93	1.6	1.46	1.03	0.83	0.70
Western Europe (11)[1]	1.34	1.2	1.14	0.94	0.83	0.70
Central Europe (12)[1]	2.09	1.7	1.53	1.05	0.83	0.70
Turkey (13)[1]	1.93	1.6	1.46	1.03	0.83	0.70
Ukraine+ (14)[1]	2.58	2.0	1.76	1.11	0.83	0.70
Central Asia (15)[1]	2.58	2.0	1.76	1.11	0.83	0.70
Russia+ (16)[1]	2.58	2.0	1.76	1.11	0.83	0.70
Middle East (17)[1]	1.93	1.6	1.46	1.03	0.83	0.70
India (18)[2]	2.91	2.2	1.91	1.14	0.83	0.70
Korea (19)[2]	1.48	1.3	1.22	0.96	0.83	0.70
China (20)[2]	3.08	2.3	1.99	1.16	0.83	0.70
South Eastern Asia (21)[1]	1.93	1.6	1.46	1.03	0.83	0.70
Indonesia (22)[1]	1.93	1.6	1.46	1.03	0.83	0.70
Japan (23)[2]	1.63	1.4	1.30	0.98	0.83	0.70
Oceania (24)[1]	2.09	1.7	1.53	1.05	0.83	0.70
Other South Asia (25)[1]	2.09	1.7	1.53	1.05	0.83	0.70
Other South Africa (26)[1]	1.93	1.6	1.46	1.03	0.83	0.70

[1] Column for 1980 based on aggregated EEI for the total industry from Groenenberg (2002).
[2] Column for 1980 based on EEI for the iron and steel industry (Table 5-4).
[3] Using the yearly efficiency improvements until 2050 are calculated with Equation 5-3, resulting in an EEI level of 0.83 in 2050.
[4] Based on Groenenberg (2002), see note 1 and 2 for details.
[5]Based on data for 2030 for the advanced BOF, the advanced EAF and the DRI route distinguished by Hidalgo et al. (Table 5-1), we calculate an EEI of 0.88 (scrap-EAF), 0.84 (pig iron-BOF), and 0.91 (DRI-EAF) compared to the levels given in Table 5-5. We took the average between these three values, corresponding to a yearly efficiency improvement of 0.32% for the best practice level. For the other region, we assume convergence to best practice levels in 2050 (see note 4).
[6]Assuming an energy efficiency improvement of 0.32% per year for the best practice level. For the other regions, yearly efficiency improvements until 2050 are calculated with Equation 5-3, resulting in an EEI level of 0.83 in 2050.
[7]Assuming an energy efficiency improvement of 0.32% per year.

5.4.2 CO_2 emissions

In the baseline scenario projections, we use a simple assumption regarding the emission factors associated with the fuel and electricity use. Coal is the main input into pig iron production and we therefore assume an emission factor of 95 kg CO_2 / GJ for the fuel input into the pig iron basic oxygen furnace route (IPCC/IEA/OECD/UNEP, 1997). The production of direct reduced iron is nowadays for 90% based on natural gas (Section 4.3.4) and we therefore assume an emission factor of 56 kg CO_2 for the fuel use in this route (IPCC/IEA/OECD/UNEP, 1997). For simplicity, we also assume natural gas to be the main fuel used in scrap based electric arc furnaces. The emissions associated with electricity vary very much per region. In the current version of the model, we use a uniform and constant emission factor of 137 kg CO_2 / GJ_e based on the worldwide energy balance for 2002 (IEA, 2004), because we are in this study not interested in efficiency improvements and fuel switches on the energy supply side. An overview of our basic assumptions is presented in Table 5-7.

Table 5-7 Emission factors assumed for the fuel and electricity use in the three routes

Route	**Emission factor fuel use (kg CO_2 / GJ)**	**Emission factor electricity use (kg CO_2 / GJ_e)**
1 PI-BOF	93	137
2 DRI-EAF	56	137
3 scrap-EAF	56	137

We would like to emphasise that these emission factors represent a very rough baseline assumption for the calculation of CO_2 emissions.

6 Derived historical model results

6.1 Scrap use and derived obsolete scrap recovery rate

In Figure 6-1 we show the total scrap consumption in the USA as calculated based on our model (Equation 4-3) and from two other sources (Kelly and Fenton, 2004a) and WSD (2005). In Figure 6-2, we do the same for the world. A subdivision into circulating, prompt and obsolete scrap is given in Figure 6-3 and Figure 6-4.

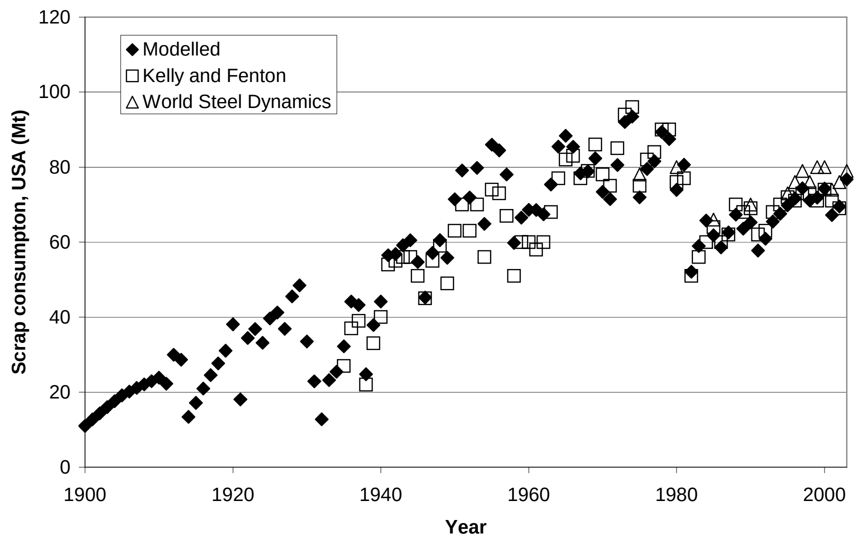


Figure 6-1 **Total scrap use in the US, 1900-2003, comparison between model outcome and other sources**

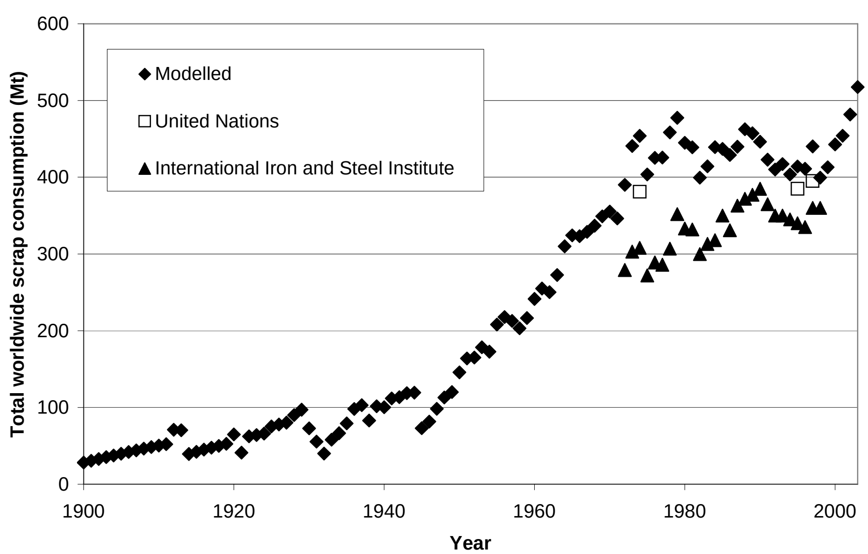


Figure 6-2 **Total worldwide scrap use, 1900-2003**

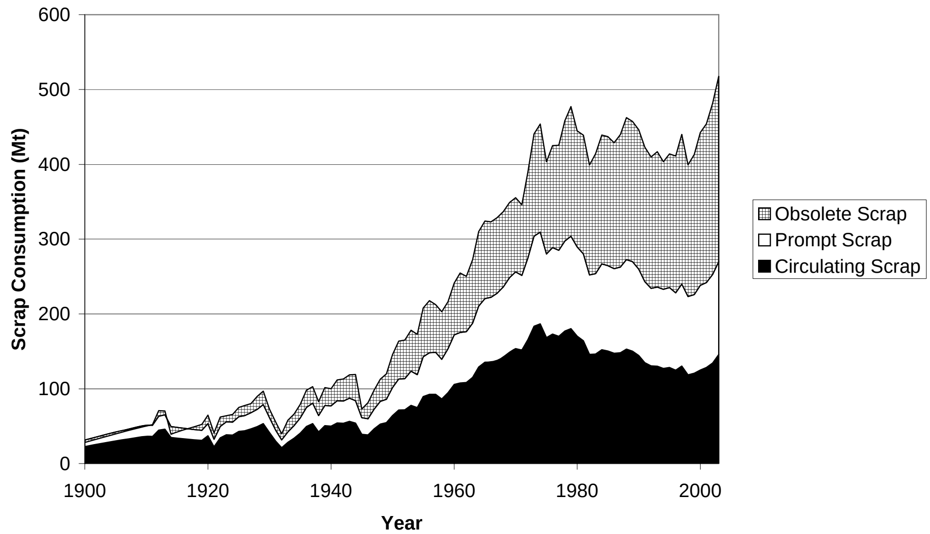


Figure 6-3 Worldwide circulating, prompt and obsolete scrap use

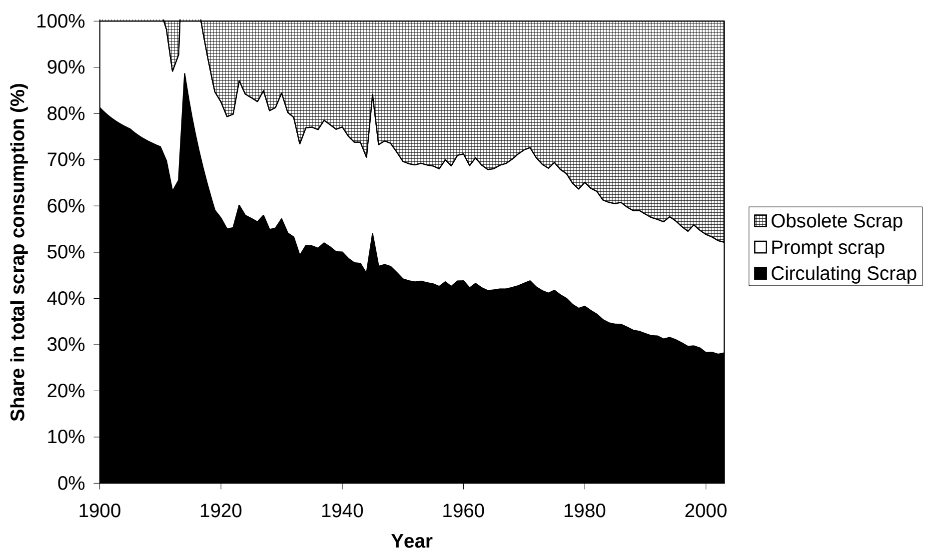


Figure 6-4 Contribution of circulating, prompt and obsolete scrap use to total worldwide scrap use

The results for the US (Figure 6-1) fit very well with the estimates provided by Kelly and Fenton (2004a) based on statistical data from the US Geological Survey Mineral Yearbooks and with estimates provided by World Steel Dynamics (2005), who use a similar method as in our model. Our worldwide estimates (Figure 6-2) fit reasonable well with data from the United Nations (1979, 1999). The values reported by the International Iron and Steel Institute are lower compared to our estimate. Partly this is caused by the fact that scrap consumption in iron foundries is not included in the IISI estimates and sometimes, information for a number of countries is not included. This is acknowledged in the publications by the United Nations:

The figures for scrap consumption (i.e.from IISI), however, are not very precise and are probably too low as the data are often underestimated and data for a number of countries are not included (UN, 1999):

According to the model calculations, the total circulating and prompt scrap availability already exceed the total amount of scrap required in the beginning of the simulation period (Figure 6-4 until 1920). This results from the fact that we made rough assumption about model parameters such as the fraction of cast iron compared to apparent crude steel consumption (Section 3.4.2) and specific iron requirements for steelmaking (Section 4.4.3) and assumed 100% recovery of circulating and prompt scrap. The strange peak during the two world wars can be explained by a mismatch between pig iron and crude steel production data taken from the Wirtschaftsvereinigung Stahl (2004). Figure 6-4 visualises the declining fraction of circulating and prompt scrap in the total scrap consumption.

Using Equation 4-2, one can calculate the obsolete scrap recovery rate based on the obsolete scrap required and the total amount of obsolete scrap available. We show worldwide results for the full simulation period in Figure 6-5 and results for the US in Figure 6-6. For other regions of the world, obsolete scrap recovery rates could only be calculated from 1980 onwards, because scrap trade data were not available before 1980. We show results for developed regions of the world in Figure 6-7 and for a selection of the other regions in Figure 6-8.

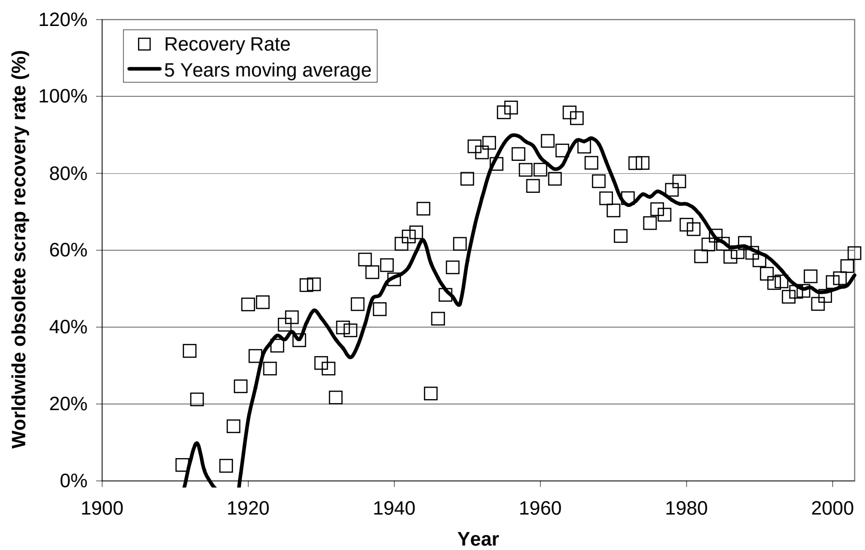


Figure 6-5 Worldwide obsolete scrap recovery rate calculated with Equation 4-2

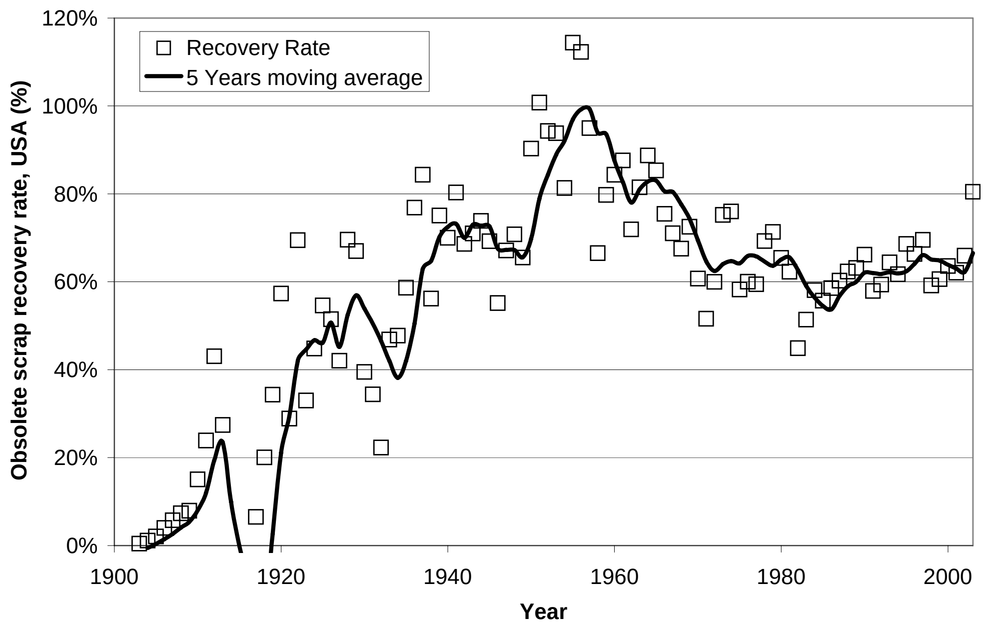


Figure 6-6 **Obsolete scrap recovery rate for the US, 1900-2003**

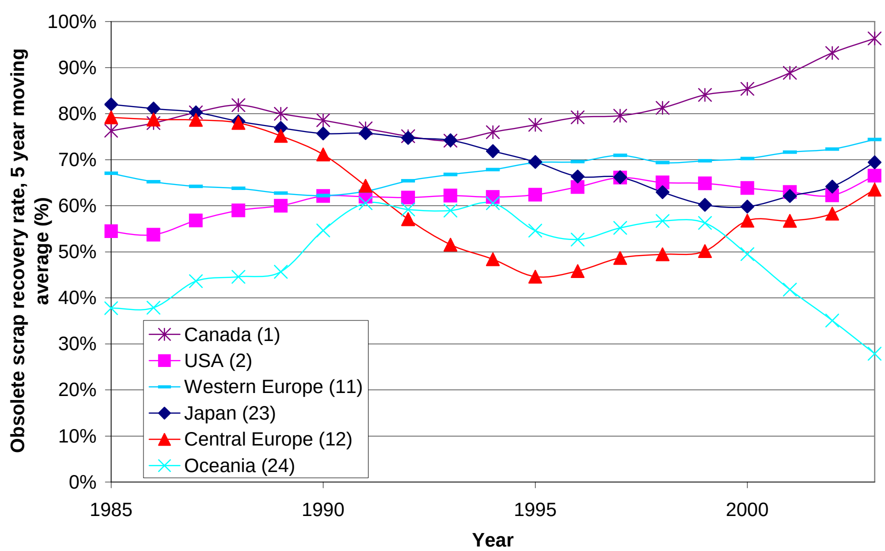


Figure 6-7 **Obsolete scrap recovery rate for developed regions, 1985-2003 (5 years moving average)**

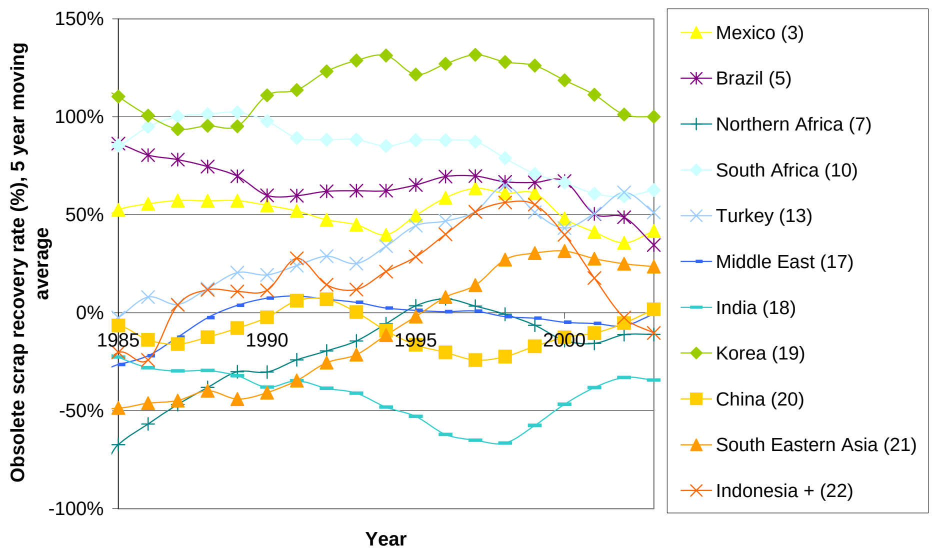


Figure 6-8 **Obsolete scrap recovery rate for a selection of other TIMER regions (5 year moving average). Small regions and regions with very small historical steel consumption omitted (region 4,6,8,9,25,26). Regions from the former USSR (14,15,16) omitted because historical consumption data per region not available.**

It is difficult to draw robust conclusions about the obsolete scrap recovery rates shown in the various figures, because of the substantial uncertainties involved in the calculation:

- The amount of obsolete scrap available is based on one uniform product distribution and a fixed lifetime distribution.
- Data on indirect trade with consumer goods containing steel is not taken into account.
- Historical trade flows for direct reduced were unavailable, resulting in too low recovery rates for direct reduced iron exporters.
- Data quality on historical steel production and steel consumption for some regions might be too weak to accurately calculate recovery rates.
- The ratio between foundry production and crude steel consumption for the US was also used for the other regions. For some regions (e.g. South Asia), the actual ratio of foundry versus apparent crude steel consumption might be much different.
- Uncertainties in the total iron input per tonne of crude steel and the circulating and prompt scrap ratios (determined in a rather generalised way) influence the obsolete scrap recovery ratios, especially for those regions that use only small amounts of obsolete scrap.

To assess these uncertainties in more detail, one needs to conduct detailed regional case studies such as the studies for the UK (Dahlstrom et al., 2004), the US (Fenton, 2004) and the EU (Moll et al., 2005) discussed in Section 4.3.7. From the study by Fenton, an obsolete recovery rate for the US in 1998 of 51% can be deducted, which is not to far off the 60% found by us (Figure 6-6). Also the 68% for the UK in 2001 found by Dahlstrom et al. and the 66% for the EU found by Moll et al. are close to the value found for Western Europe in this study (~70%). For some of the other regions, less logical results are found (Figure 6-8) with recovery rates below 0 (according to the model calculations, the circulating and prompt scrap is sufficient to cover the total scrap requirements) or above 1 (more obsolete scrap is required then apparently available).

According to Figure 6-5 and Figure 6-6, the obsolete scrap recovery rate in the 1950s and 1960s seems to be very high, although also there, the various uncertainties listed above play a

role. The fixed product and lifetime distribution used does not, for example, take into account the destruction of infrastructure during the Second World War. Still, the high obsolete scrap recovery rates might be explained by the rapid increase in crude steel consumption in the 1950s and 1960s (Figure 3-2), which resulted in an attempt to use as much iron resources as possible, including stocks of obsolete machinery etc. For the US, this is confirmed in the US Geological Survey Mineral Yearbook of 1951 (USGS, 1951):

"In order to alleviate the purchased-scrap shortage, which was caused by the mills expanding their production facilities to meet the requirements of an increased military program as well as domestic needs, the Government, through the National Production Authority, organized committees in industry to appoint representatives in their organizations to urge the collection of all dormant plant scrap and to identify machinery that was obsolete and could be scrapped. Federal Government agencies, including the Navy and Army, Maritime Commission, and the Interior and Agriculture Departments, were called upon to urge their various installations, yards, nines and experiment stations, to turn in all possible scrap".

In a publication by Birat and Zaoui (2002), the trend of a declining obsolete scrap recovery rate between 1950 and 2000 is also confirmed for the EU-12.

6.1.1 Obsolete scrap recovery rate used in projections

Based on the historical analyses given above, we conclude that for developed regions of the world, obsolete recovery rates currently amount to 60% to 80%. As the baseline scenario used for the projection, we assume an obsolete scrap recovery rate of 70%. To avoid a large trend break compared to current levels, we let the current obsolete scrap recovery rate (Figure 6-6 to Figure 6-8) converge to the 70% level between 2003 and 2020.

6.2 Stocks in use

As explained in Section 4.4.9, we calculate within the model also a number of stocks:

- Losses of iron before the iron is embodied in products. These losses result from the fact that the total iron requirements in steel production are well above 1. These losses are in the form of dust, slag etc.
- The stock of iron in use. This is the amount of iron, which is embodied in products that are still in use.
- Non-recovered obsolete scrap. This is the amount of products that according to the assumptions made is no longer in use, but is, again according to our assumptions, also not recycled as obsolete scrap.

To close the mass balance, the total of these three stocks should be balanced by the flow of primary iron into the system. Another method to calculate the total stock in use in the economy is therefore to track the cumulative production of primary iron. This method is followed by Sullivan (2005) who calculates the cumulative total primary iron production in the US and corrects for imports and exports of primary iron, scrap, steel and products containing steel to come to an estimate of the total iron stock within the US. No calculations are made for specific iron requirements per tonne of steel and for various product categories and lifetime distributions, so the distinction between the types of stocks as we do in our study is not made. However, estimates are provided for the amount of steel stored in landfills. In Figure 6-9, we compare the total according to our model with the total according to Sullivan (2005). The difference is caused by the initial stock in 1900 that is not taken into account in the Sullivan study, but is included in our study. The reason for the declining gap in the last decades is the net import of steel containing end products, which is included in the Sullivan study, but neglected in ours. In Figure 6-10, we show the division between the three types of stocks distinguished. In Figure 6-11, we add the estimate for iron and steel in landfills

estimated by Sullivan (2005). The figure shows that we are able to explain to a large extent the total flow of primary iron through the US economy with our estimates of losses, stock in use and land filled scrap. In the 2005 sustainability report of the International Iron and Steel Institute (2005b), reference is made to a Japanese study in which a total stock of 1260 Mt steel products is mentioned for Japan in 2003. With our model, we estimate a total stock of 1530 Mt. Part of the difference can be explained by the considerable net indirect export of steel (embodied in products) that seems to be taken into account in the Japanese study, but is neglected in our study.

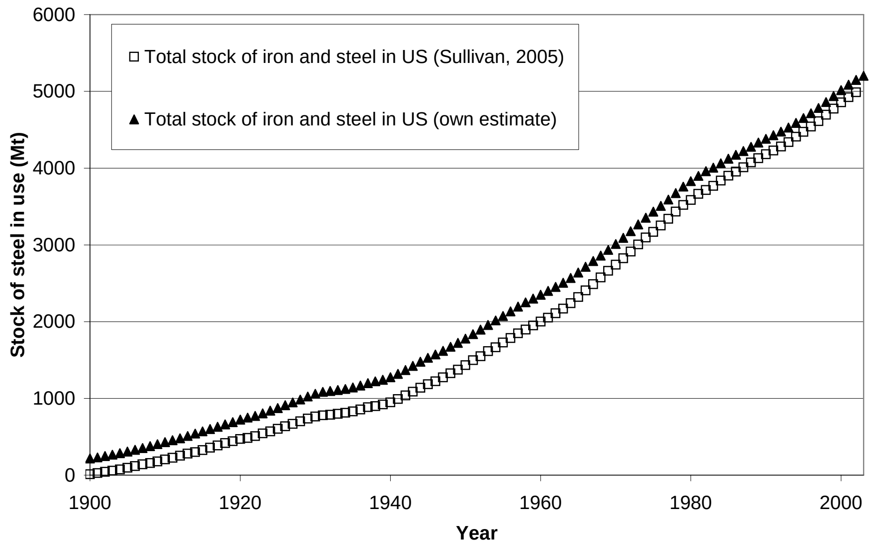


Figure 6-9 **Total stock of iron and steel in the US, comparison with estimate from Sullivan (2005)**

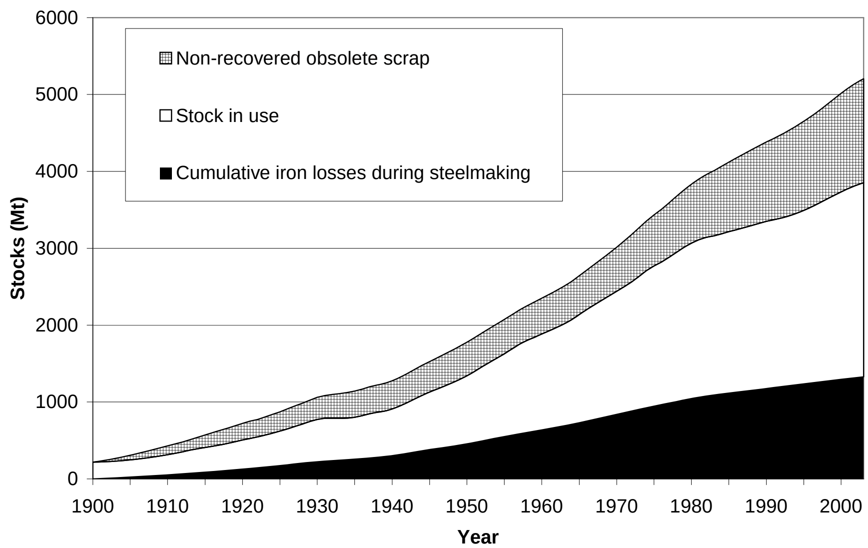


Figure 6-10 **Total stock of iron and steel in the US, comparison division into three types of stocks.**

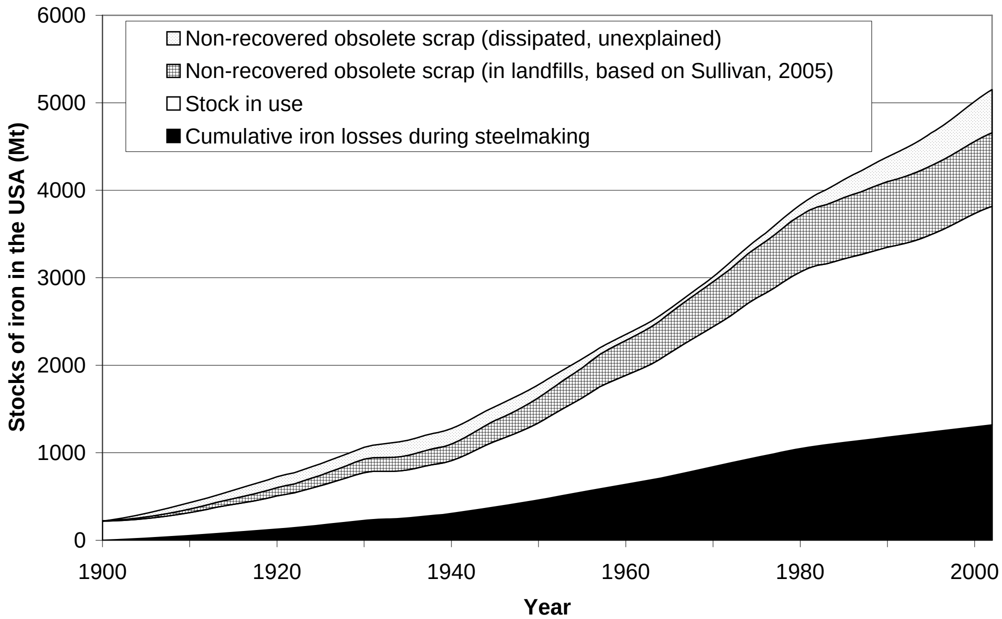


Figure 6-11 **Total stock of iron and steel in the US, including estimate for iron in landfills (Sullivan, 2005).**

6.3 Energy use and CO_2 emissions

We compare total primary energy use for some single country regions according to our model with estimates given by Kim and Worrell (2002).

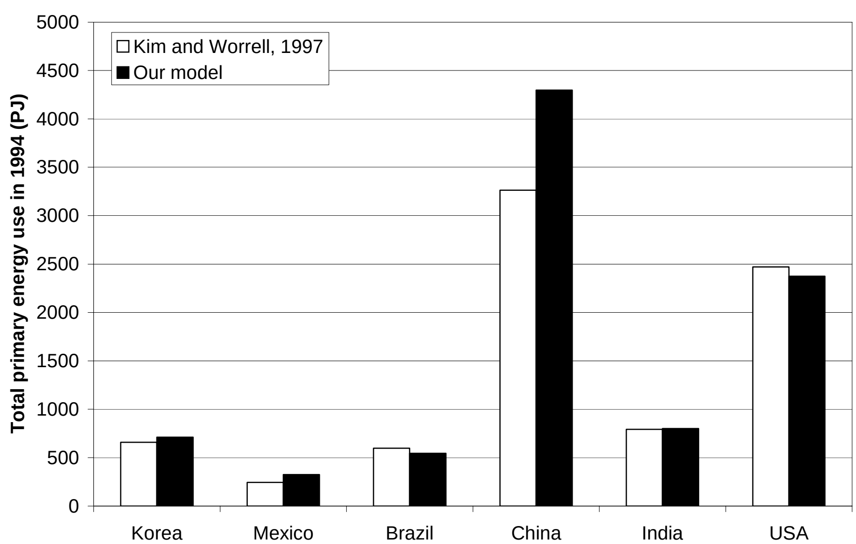


Figure 6-12 **Total primary energy use in a number of countries. Comparison between model outcome and Kim and Worrell for 1994 (Kim and Worrell, 2002).**

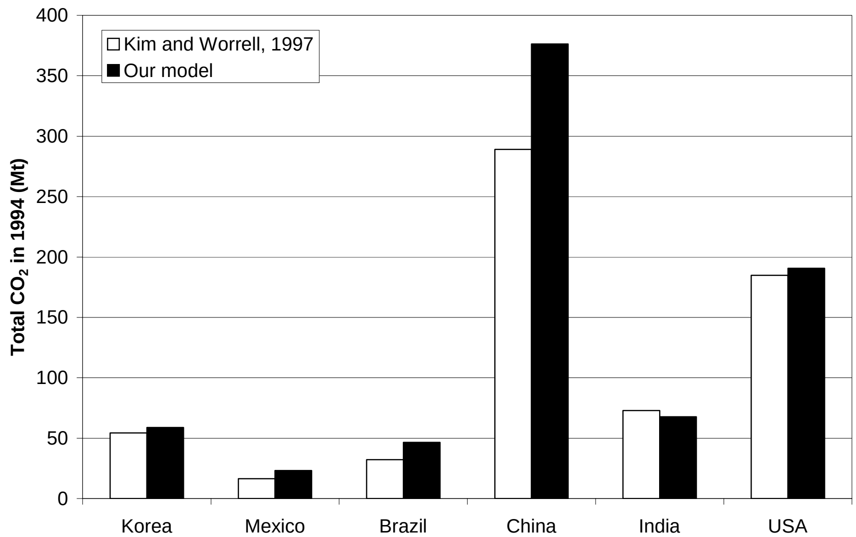


Figure 6-13 Total CO_2 emissions in a number of countries. Comparison between model outcome and Kim and Worrell (2002).

Various differences exist in the method to calculate energy use and CO_2 emissions used by Kim and Worrell (2002) and the method used in this study. Energy use and CO_2 emissions for coke making are for example not included in the Kim and Worrell study, whereas they are included in the current study. Also the assumptions related to indirect emissions from electricity production differ between the Kim and Worrell study and our study. Still, we conclude that our model enables the calculation of total primary energy use and CO_2 emissions reasonably well.

Another valuable comparison would be to compare on a regional level with the international energy statistics published by the International Energy Agency (2004). This comparison has been made as part of a follow-up project focused on the incorporation of the model results into TIMER (Roorda, 2006). The study revealed that the IEA statistics can not directly be used for model purposes, because of the limited data quality.

7 Scenario projections and conclusions

7.1 Introduction and scenario description

In this chapter, we project steel consumption, steel production and associated energy use and CO_2 emissions until 2100 using the model described in the previous chapters and compare the results with other available projections. For practical reasons, we show in some cases results for 10 instead of 26 world regions:

North America (regions 1 and 2)
Central and South America (regions 3-6)
Africa (regions 7-10 + 26)
Europe (regions 11 + 12)
Turkey and the Middle East (regions 13 and 17)
Former USSR (regions 14-16)
India (region 18)
Korea and China (region 19 and 20)
Other Asia (regions 21, 22 and 25)
Japan and Oceania (regions 23 and 24)

The demographic (population) and economic (GDP/capita) exogenous input parameters that determine steel demand are directly taken from the TIMER model (see Appendix 3). Four scenario storylines for the future demographic and economic development of the world are distinguished: the A1, A2, B1 and B2 storylines, described in detail in a publication by the Intergovernmental Panel on Climate Change (IPCC) on Emission Scenarios (Nakicenovic, 2000). The storylines also include statements on the development of trade and the development of energy efficiency and the penetration of new technologies. In our baseline scenario projections (Section 7.2 − Section 7.4), however, we only include the population and economic projections according to the four scenarios and use the default assumptions for trade and energy efficiency described in the previous chapters. In Section 7.5, we separately discuss the effects of different assumptions regarding trade and energy efficiency on the projected results. The population and GDP projections according to the four scenarios are presented in Figure 7-1 and Figure 7-2. The narrative storylines of the four scenarios are summarised in Appendix 5.

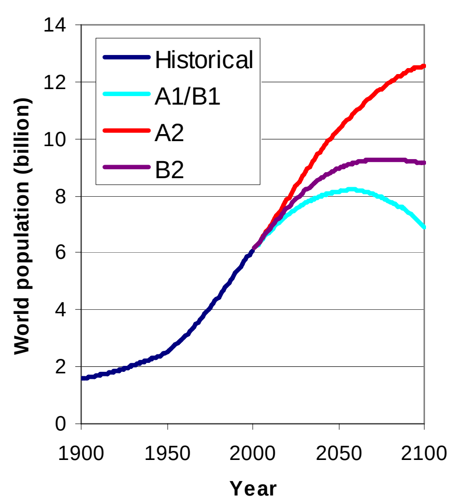


Figure 7-1 Historical and projected world population in the four scenarios

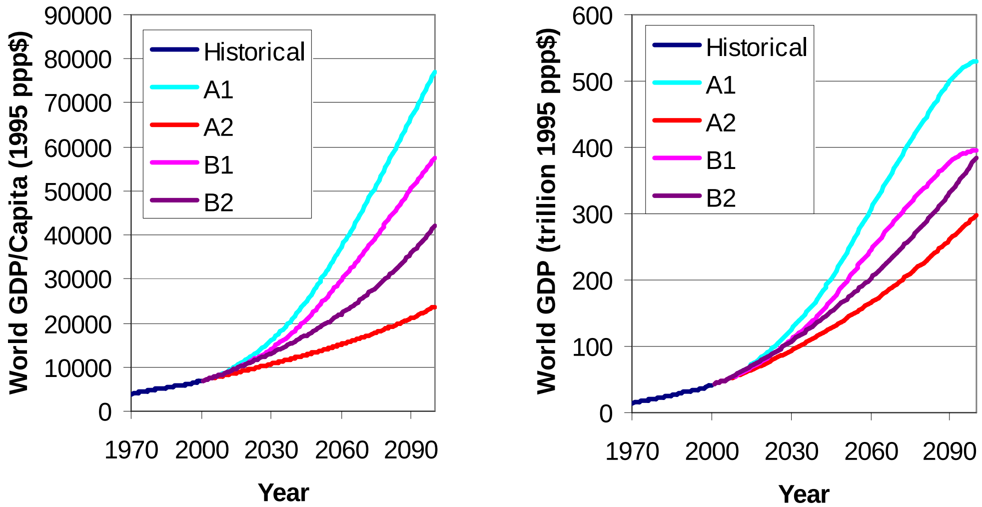


Figure 7-2 Historical and projected world GDP estimates (1995 ppp $)

7.2 Steel consumption

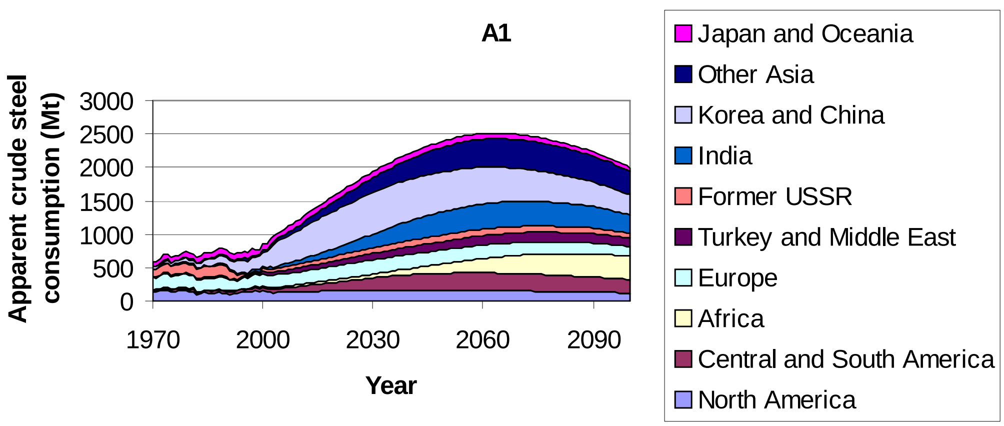
The exogenous assumptions on GDP/capita and population development in combination with the intensity of use curves described in Chapter 3 yield the projections for apparent crude steel consumption given in Figure 7-3. In the A1 and B1 scenarios, steel consumption is projected to increase to a maximum of 2510 and 2342 Mt respectively (NB, current consumption is approximately 1000 Mt), followed by a decline induced by a declining population and improvements in material efficiency. In the A2 scenario, steel consumption increases to 2500 Mt in 2100, mainly as a result of a continuously increasing population (Figure 7-1). In the B2 scenario (which can be regarded as an 'average' scenario with average income and population growth), apparent crude steel consumption reaches a maximum of 2350 Mt near the end of the century. Total worldwide steel consumption in the four scenarios is quite similar. This results from the fact that the scenarios with relatively high economic growth (A1, B1) have relatively small population growth, whereas the scenarios with smaller economic growth have a larger population growth. The two effects have an opposite effect, resulting in similar total worldwide consumption levels.

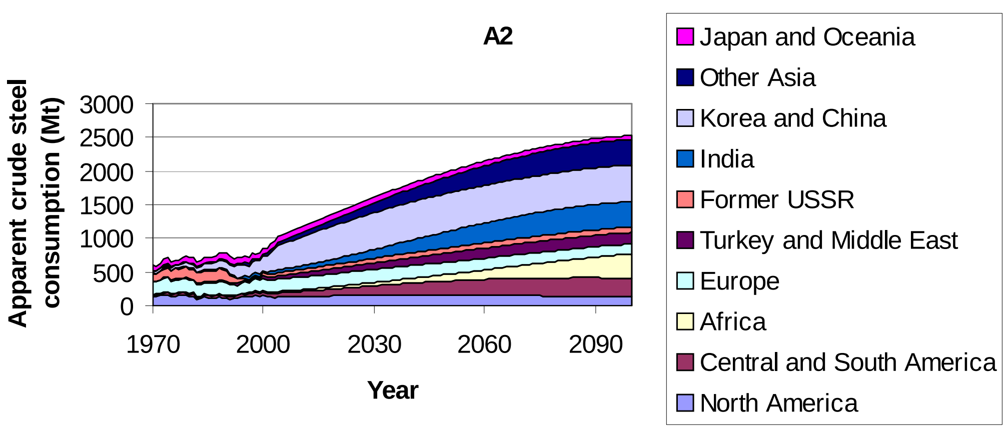
The different projections for economic growth (Figure 7-2) do result, however, in quite different average worldwide per capita crude steel consumption levels, shown in Figure 7-4. An illustrative example (for the B2 scenario) on the regional development of per capita apparent crude steel consumption is presented in Figure 7-5. Both the saturation and the material efficiency effect are clearly visible.

Hidalgo et al. (2005) project in their IPTS model an apparent worldwide crude steel consumption of 1316 Mt in 2030, whereas our projection ranges between 1610 (A2) and 1934 (A1) Mt. In the VLEEM model (2005), a consumption level of 1977 Mt in 2030 is projected (Table 7-1). Due to differences in regional classification, the comparison on a regional level is not easy to make, especially with the VLEEM model. We can still draw some conclusions. In the IPTS model, consumption levels of regions with high per capita consumption levels (EU-15, North America, Pacific OECD, South Korea) are projected to drop in the coming decades, whereas we project a stabilisation or slight increase. In some cases (South Korea, Pacific OECD), steel consumption in the IPTS model even drops by more than a factor 2. The rationale behind this drop is not further explained.

For Africa and Middle East and Economies in transition and the Rest of Asia, we project steel consumption comparable to the IPTS model. For China, Latin America and India, we project consumption levels much higher than the IPTS model (except for the B2 scenario for India). The difference for China explains already 150-250 Mt of the gap between the IPTS model and our projections and it should be noted that the IPTS model was made before the 'explosion' in the Chinese steel consumption at the start of this century. As a result, the projected consumption levels in 2030 in the IPTS model are only 20% above the apparent crude steel consumption level in 2003. In the VLEEM model, a higher development rates and as a result higher consumption rates are projected for Africa and the Middle East and for India. Steel consumption in China is somewhat lower. In the VLEEM model, the same mathematical equation is used to project steel consumption as in our model, but no material efficiency factor is included and slightly different regional fits are used. Because of the absence of a material efficiency factor, steel consumption in the VLEEM model keeps on increasing to the end of the simulation period (2100) and reaches a level of nearly 4000 Mt in 2100 in the VLEEM model, while in our model steel consumption in 2100 is at most 2500 Mt. In Section 7.5, we will further discuss the effect of different material efficiency factors on steel demand.

In a recent paper, Gielen and Podkanski (2006), project steel demand to grow to 1700 and 2250 Mt in 2050 under a 'low-demand' and 'high-demand' scenario, whereas we project a worldwide demand of 1989-2403 Mt.





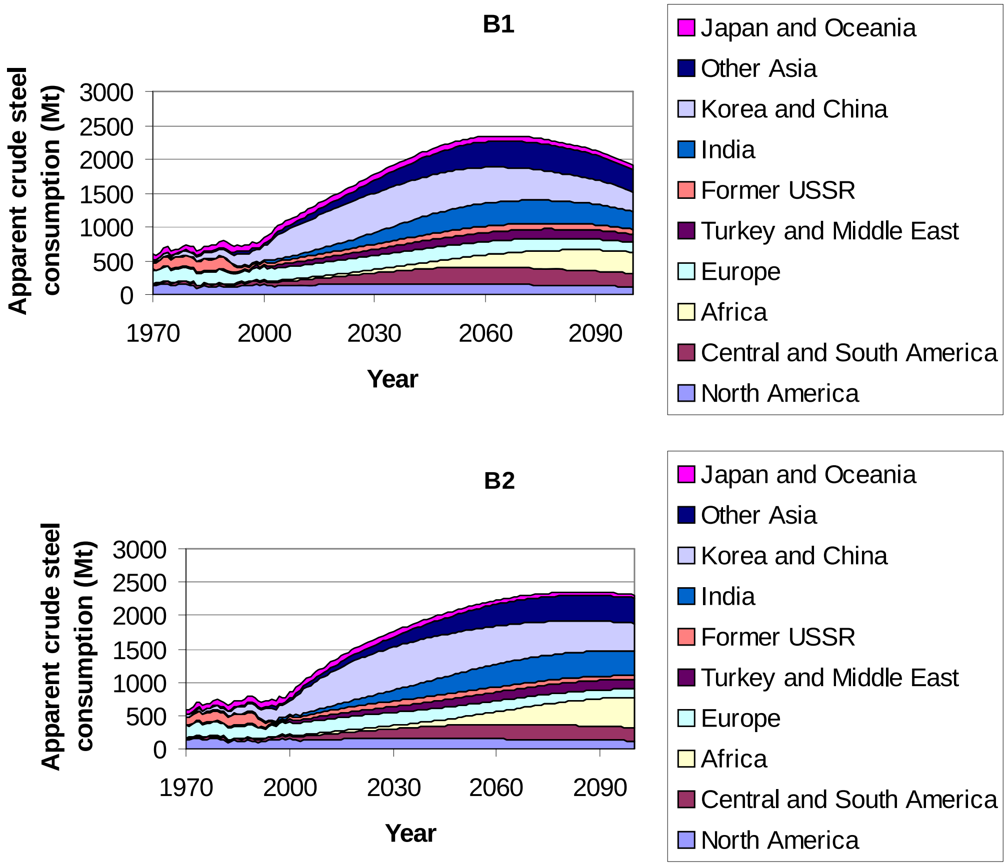


Figure 7-3 **Apparent crude steel consumption in the 26 TIMER regions under the four demographic and economic scenarios**

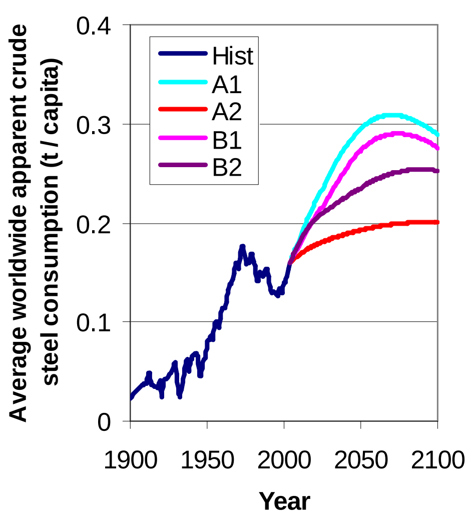


Figure 7-4 **Average worldwide apparent crude steel consumption per capita under the four demographic and economic scenarios**

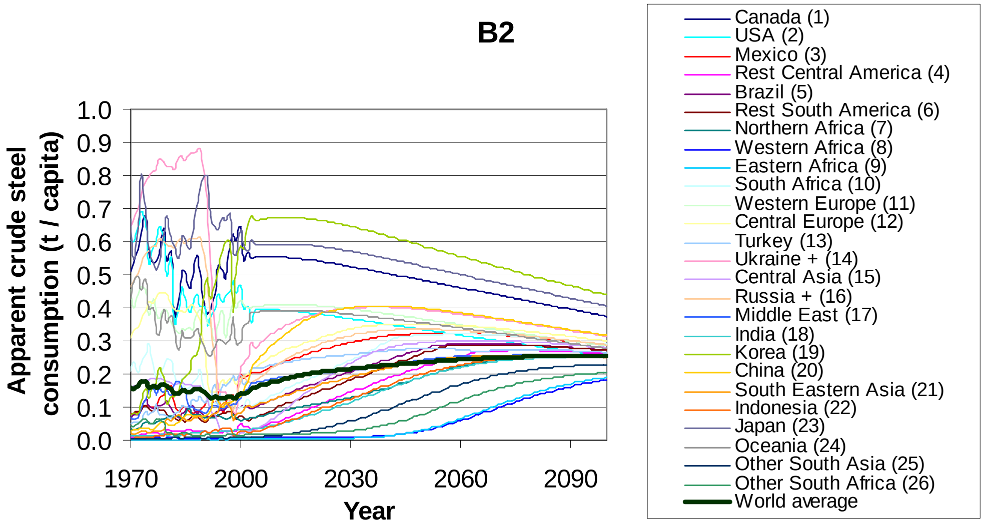


Figure 7-5 Apparent crude steel consumption per capita in the B2 scenario

Table 7-1 Comparison of apparent crude steel consumption in Mt in the IPTS and VLEEM models and our model

Region	**TIMER region**[1]	**2003**	**2030 IPTS**[2]	**2030 Vleem**[3]	**2030 Our model A1**	**2030 Our model A2**	**2030 Our model B1**	**2030 Our model B2**
Africa and Middle East	7-10, 26	51	120	276	129	115	113	109
China	20	286	349	439	574	503	538	598
Economies in transition	12, 14-16	75	120	*73*	129	105	118	121
EFTA and Turkey	13	15	*24*		25	27	24	24
EU-15	11	157	*108*	*279*	168	157	166	157
India	18	35	132	*281*	205	130	168	162
Latin America	3-6	53	120	127	186	143	162	145
North America	1,2	121	108	205	157	152	155	154
Pacific OECD	23,24	87	42	*134*	90	84	89	81
Rest of Asia	21,22,25	41	*174*	*163*	222	145	187	153
South Korea	19	48	*18*		48	45	47	49
World		970	1316	1977	1934	1606	1767	1754

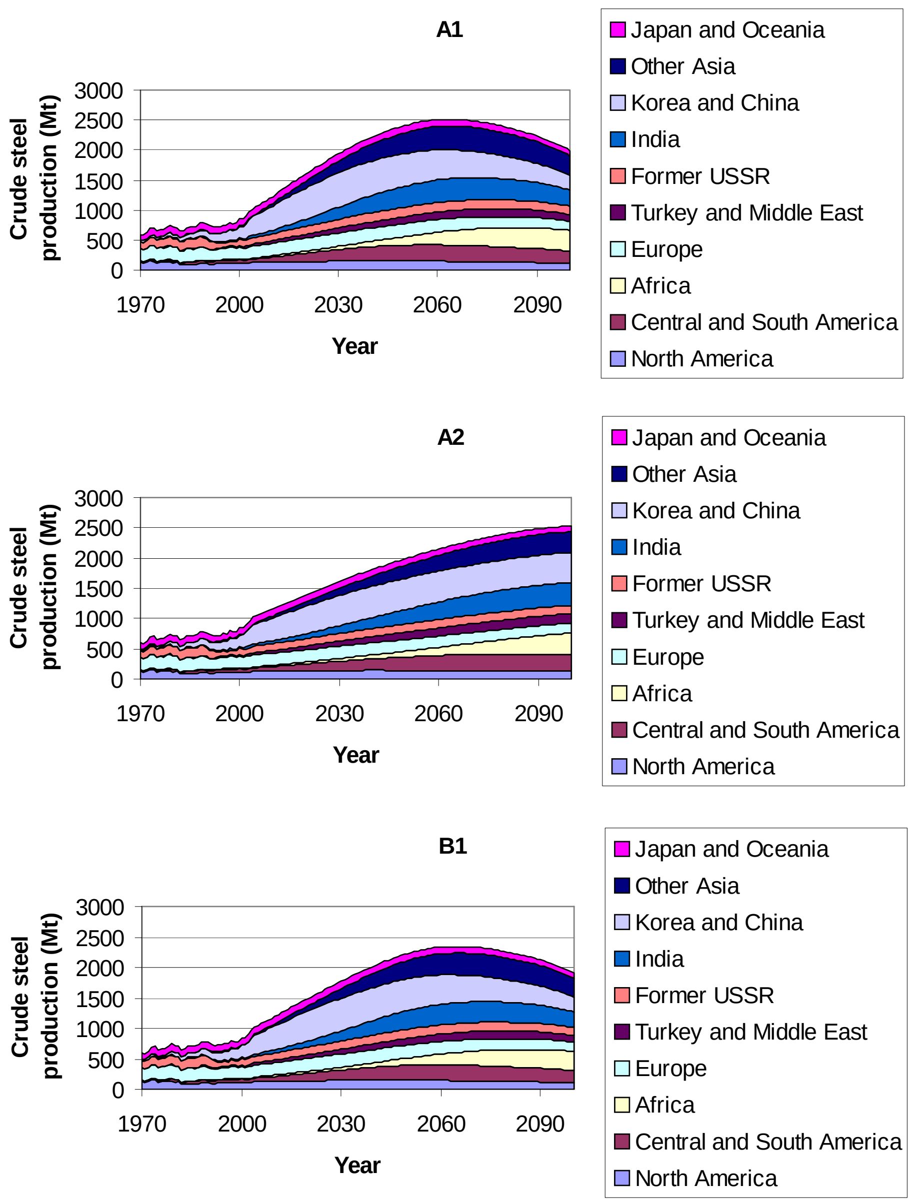
[1] The comparison for EU-15, EFTA and Turkey, Rest of Asia and South Korea is not fully valid. EFTA countries are in our model included in Western Europe. Korea in our model also included North Korea, whereas it is included in the Rest of Asia in the IPTS model. Incomparable data are given in italics.
[2] Consumption figures in the IPTS model are given as finished steel consumption. We converted to apparent crude steel consumption figures using a multiplication factor of 1.2, derived from the difference between crude steel production and finished steel production in the IPTS model.
[3] VLEEM region South Asia given under India. Former USSR given under economies in transition. Other Asia pacific given under Rest of Asia. South Korea included in Pacific OECD region. EU-33 given under EU-15.

7.3 Steel production, trade and stock of iron in use

7.3.1 Steel production and trade

In the default steel trade scenario, we freeze the absolute trade flows at 2003 levels. Alternative trade scenarios are presented in Section 7.5.2. The relative trade (as percentage of apparent crude steel consumption) that results from this trade assumption is presented in Appendix 7. For currently low developed regions of the world that experience significant growth in apparent crude steel consumption and are currently net importers of semi-finished

and finished steel product, the net import declines in the coming century. In none of the scenarios, the relative net import of any region is higher than 20% in 2100. For countries with stable or declining apparent crude steel consumption, relative trade remains stable or even increases over time. As a result, regions that are currently significant net exporters of semi-finished and finished steel (Ukraine+, Russia+, South Africa, Japan) remain so over time. The crude steel production resulting from the trade assumptions is presented in Figure 7-6, a comparison with the VLEEM and IPTS models in Table 7-2. The largest differences exist between the production projections according to our model and according to the IPTS model exist for India and China. The differences for those two regions explain between 200 (A2 scenario) and 371 Mt (A1 scenario) of the differences between the two models. The higher development rates assumed for Africa and the Middle East and for India result also in higher estimates for steel production in those regions in the VLEEM model.



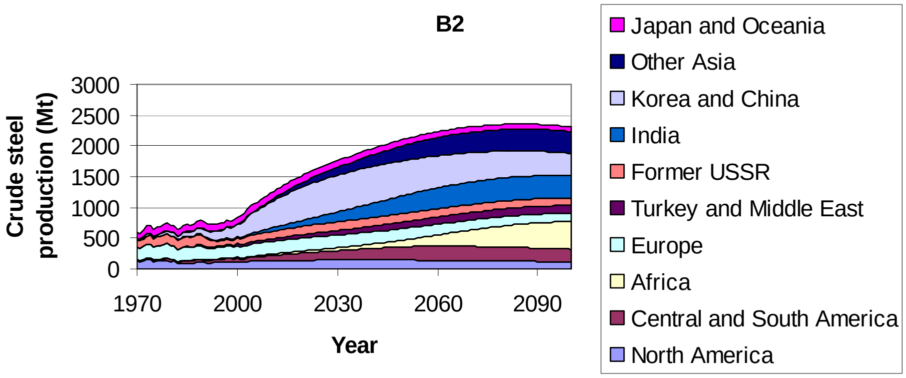


Figure 7-6 **Crude steel production in the 26 TIMER regions under the four demographic and economic scenarios**

Table 7-2 **Comparison of crude steel production in the IPTS and VLEEM models and our model**

Region	**TIMER Region[1]**	**2003**	**2030 IPTS**	**2030 Vleem[2]**	**2030**	**2030**	**2030**	**2030**
						Our model		
					A1	**A2**	**B1**	**B2**
Africa and Middle East	7-10, 26	30	80	279	108	96	94	90
China	20	239	302	442	526	456	490	551
Economies in transition	12, 14-16	140	185	*65*	194	170	184	187
EFTA and Turkey	13	18	*25*		28	30	27	27
EU-15	11	162	*155*	*291*	173	162	171	162
India	18	32	65	*281*	202	127	165	159
Latin America	3-6	60	135	126	193	150	169	152
North America	1,2	113	155	157	149	144	147	146
Pacific OECD	23,24	119	85	*166*	122	115	121	113
Rest of Asia	21,22,25	12	*85*	*170*	193	116	158	124
South Korea	19	47	*45*		47	44	46	48
World		971	1317	1977	1936	1609	1770	1757

[1] The comparison for EU-15, EFTA and Turkey, Rest of Asia and South Korea is not fully valid. EFTA countries are in our model included in Western Europe. Korea in our model also included North Korea, whereas it is included in the Rest of Asia in the IPTS model. Incomparable data are given in italics.

[2]VLEEM region South Asia given under India. Former USSR given under economies in transition. Other Asia pacific given under Rest of Asia. South Korea included in Pacific OECD region. EU-33 given under EU-15.

7.3.2 Scrap availability, steel production by technology

We project an increasing amount of obsolete scrap to become available in the future as a result of an increased worldwide steel consumption, although there is a substantial delay between consumption and availability as prompt scrap for a large fraction of the total steel consumed (e.g. 35% of steel is assumed to go to applications having an average lifetime of 70 years, Section 4.4.6). The total share of secondary inputs into steel production according to the four scenarios is given in Figure 7-10, resulting in the technology shares given in Figure 7-10 using the assumptions described in Section 4.4.2. The trend break visible in 2020 in Figure 7-7 results from the fact that we let the obsolete scrap recovery rate converge from current levels (Figure 6-5 to Figure 6-8) to 70% between now and 2020.

As a result of the model dynamics, significant difference exist in the regional shares of secondary inputs in total crude steel production. As an example, we show the shares for the B2 scenario in Figure 7-8. Two types of regions have a low share of secondary inputs into crude steel production:

- Regions with a large relative net export of steel (Ukraine, Russia, South Africa, Brazil). In those regions, domestic steel consumption is much lower than domestic steel production and the crude steel produced therefore becomes obsolete scrap in another region. Since we do not include scrap trade in our projections, this results in a low share of secondary inputs.
- Regions with a still increasing crude steel production in 2100 (African regions and South Asia). As a result of the delay between steel consumption and the occurrence as obsolete scrap, the availability of obsolete scrap is still low compared to the steel production.

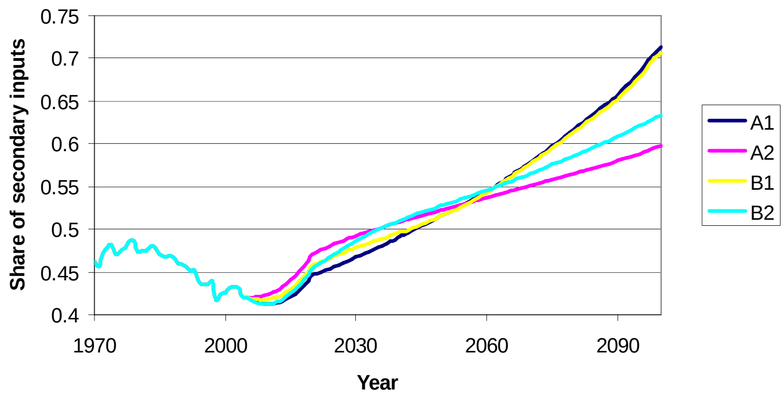


Figure 7-7 **Worldwide share of secondary inputs into crude steel production and production in iron foundries under the four demographic and economic scenarios**

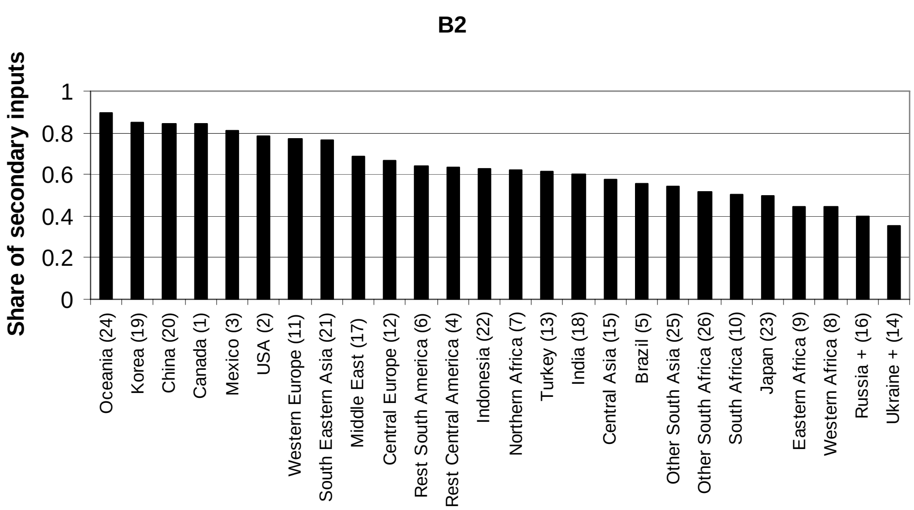


Figure 7-8 **Share of secondary inputs into crude steel and iron foundry in 2100 in the B2 scenario**

The share of obsolete scrap in total scrap use further increases over time at the expense of circulating and prompt scrap. As an example, we show the shares of circulating, prompt and obsolete scrap in total scrap use in the B2 scenario in Figure 7-10.

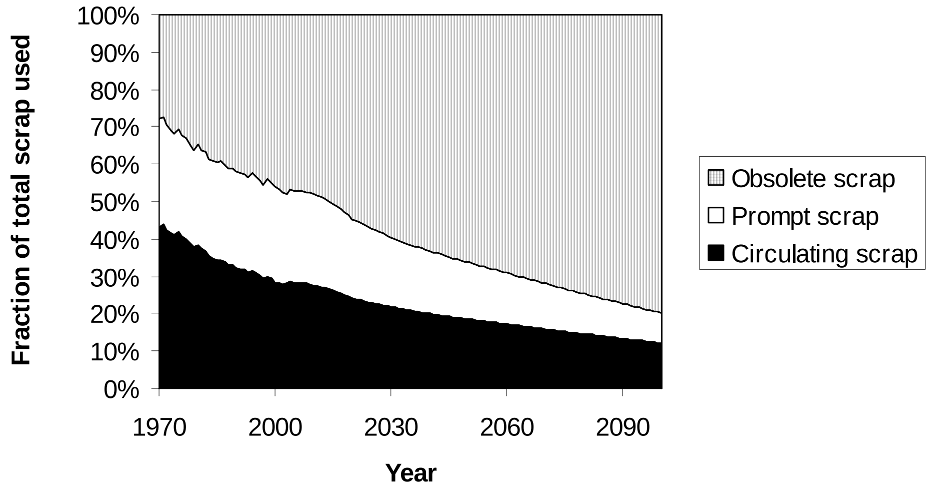


Figure 7-9 Worldwide share of circulating, prompt and obsolete scrap in total scrap use in the B2 scenario

Using the assumption of a frozen share of direct reduced iron in total primary iron production per region (Section 4.4.2), the share of the three technologies distinguished is determined. The results for the world for the four scenarios are presented in Figure 7-10. Scrap based electric arc furnaces reach a market share of 52% (A2) to 65% (A1) in 2100. Direct reduced iron based electric arc furnaces gain a market share of approximately 10% (currently 4%), because primary production increases more rapidly in those regions where direct reduced iron has a high share in primary iron production (Figure 4-15) than in regions where no direct reduced iron is produced. The remainder of the steel production is produced via the pig iron – basic oxygen furnace route. The share of scrap based electric arc furnace production (based on the modelled availability of scrap) is equal (scenario A2) or somewhat higher (other scenarios) than the 52% projected in the VLEEM model (2005), where the fraction of secondary steel is an exogenous input to the model. By 2030, electric arc furnaces (both based on scrap and on direct reduced iron) have a worldwide market share of 47%, which is almost equal to the 45% projected in the IPTS model based on cost price comparisons[19].

[19] In which an exogenous scrap price is used.

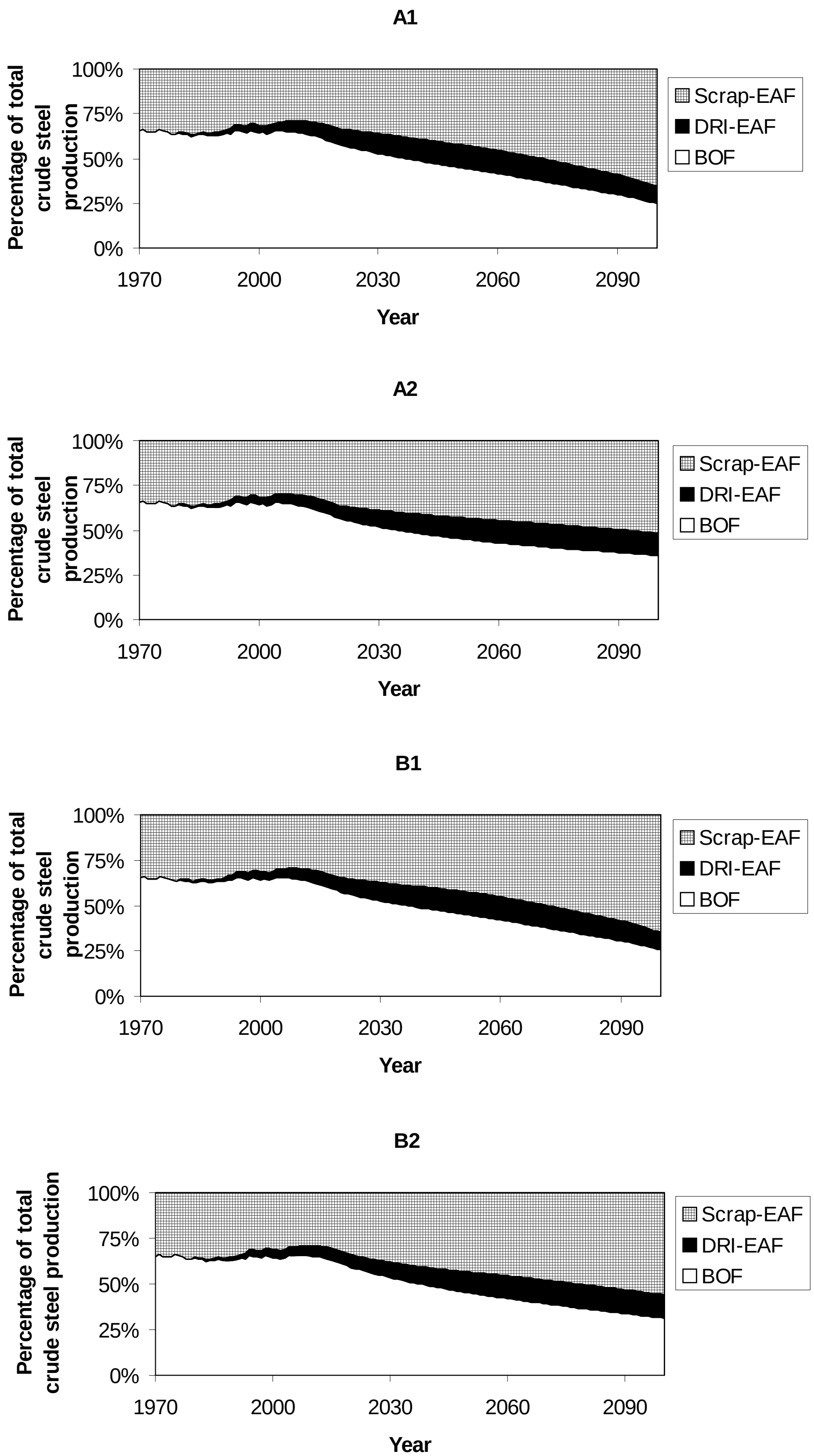


Figure 7-10 Worldwide shares of technologies in crude steel production

7.3.3 Stocks of iron in use

The model allows calculating the stock of iron and steel products in use. As a result of the assumed saturation level of the apparent crude steel consumption per capita at high-income levels, the steel stock in use finally also saturates, but, due to the long lifetime of certain steel products, there is a significant time gap between saturation of the steel demand and saturation of the stock in use. Under the four scenarios, the steel stock in use increases from approximately 2 Mt per capita nowadays to between 5 and 10 Mt / capita in 2100 (Figure 7-11). An example of the regional development of the stock in use is given in Figure 7-12. The development of the stock in use could also be used as the driver of steel demand (Mueller, 2005). We will further discuss this in the final chapter of this study.

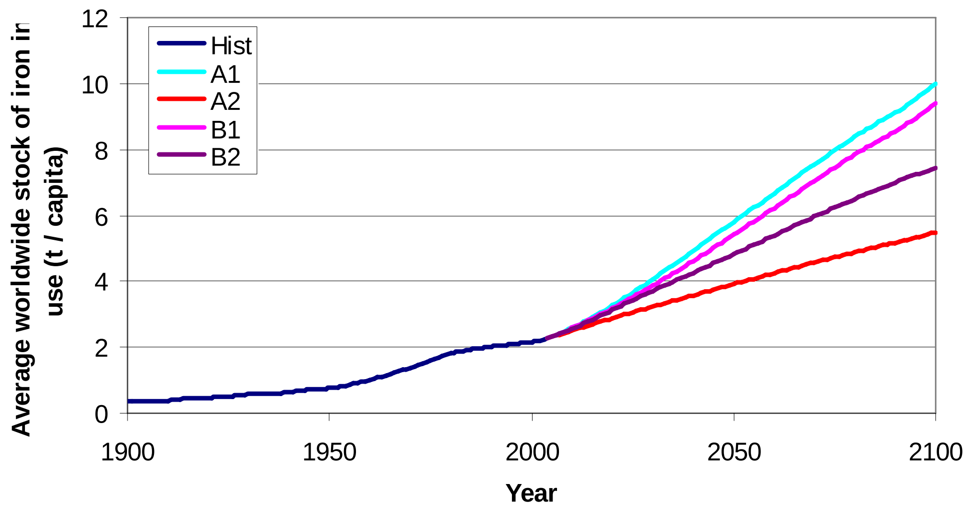


Figure 7-11 Worldwide stock of steel in use (t / capita) under the four demographic and economic scenarios

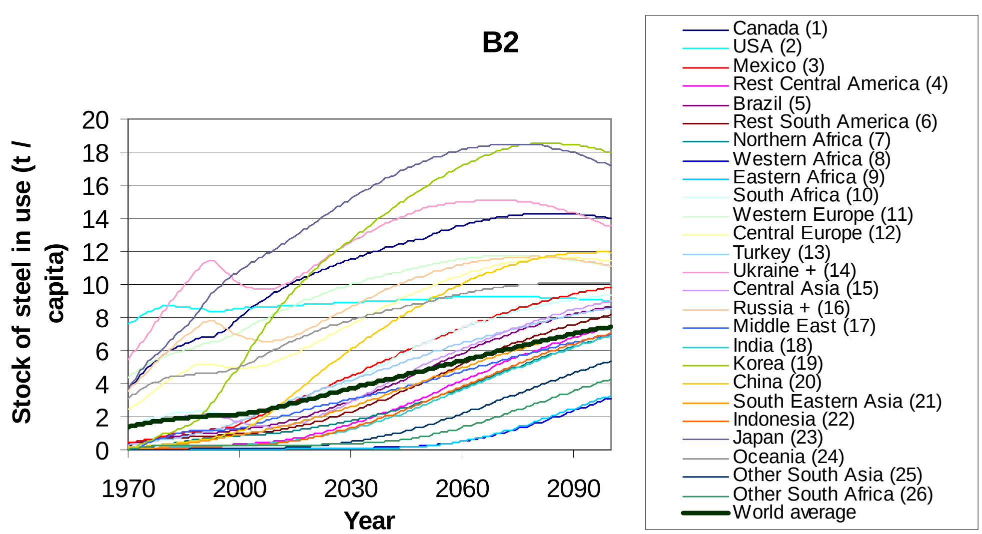


Figure 7-12 Stock of iron in use (t / capita) for the B2 scenarios

7.4 Energy use and CO_2 emissions

Projected energy use and CO_2 emissions are given in Figure 7-13 and Figure 7-14. As a result of energy efficiency improvements, total worldwide primary energy use peaks much earlier than worldwide steel consumption at levels between 30 and 40 EJ and 2000 and 2500 Mt CO_2 respectively. In the VLEEM model, the same peak value is projected for total primary energy use[20], but total primary energy use is higher towards the end of the century than in our projections as a result of the higher projected steel consumption and production. Primary energy use in 2030 according to IPTS model is about 20000 PJ, whereas we project a total worldwide primary energy use in 2030 of 30000 (A2 scenario) to 37000 PJ (A1 scenario), 1.5 to 1.85 times as much.

This is also reflected in total CO_2 emissions from fuel use[21] projected by our model, compared to the IPTS model (Table 7-3). Partly, this is the result of the smaller production levels according to the IPTS model (our crude steel production projection are 1.22 to 1.33 times higher than the IPTS estimate), but partly, it is also the result of a faster introduction of new technologies in the IPTS model, especially in China. In our model (Section 5.4), technological convergence takes place relatively slowly. In the next section, we will discuss some alternative assumptions with respect to energy efficiency developments.

[20] In the VLEEM model, no CO_2 emissions are calculated
[21] In the IPTS model, no indirect CO_2 emissions from electricity use are calculated

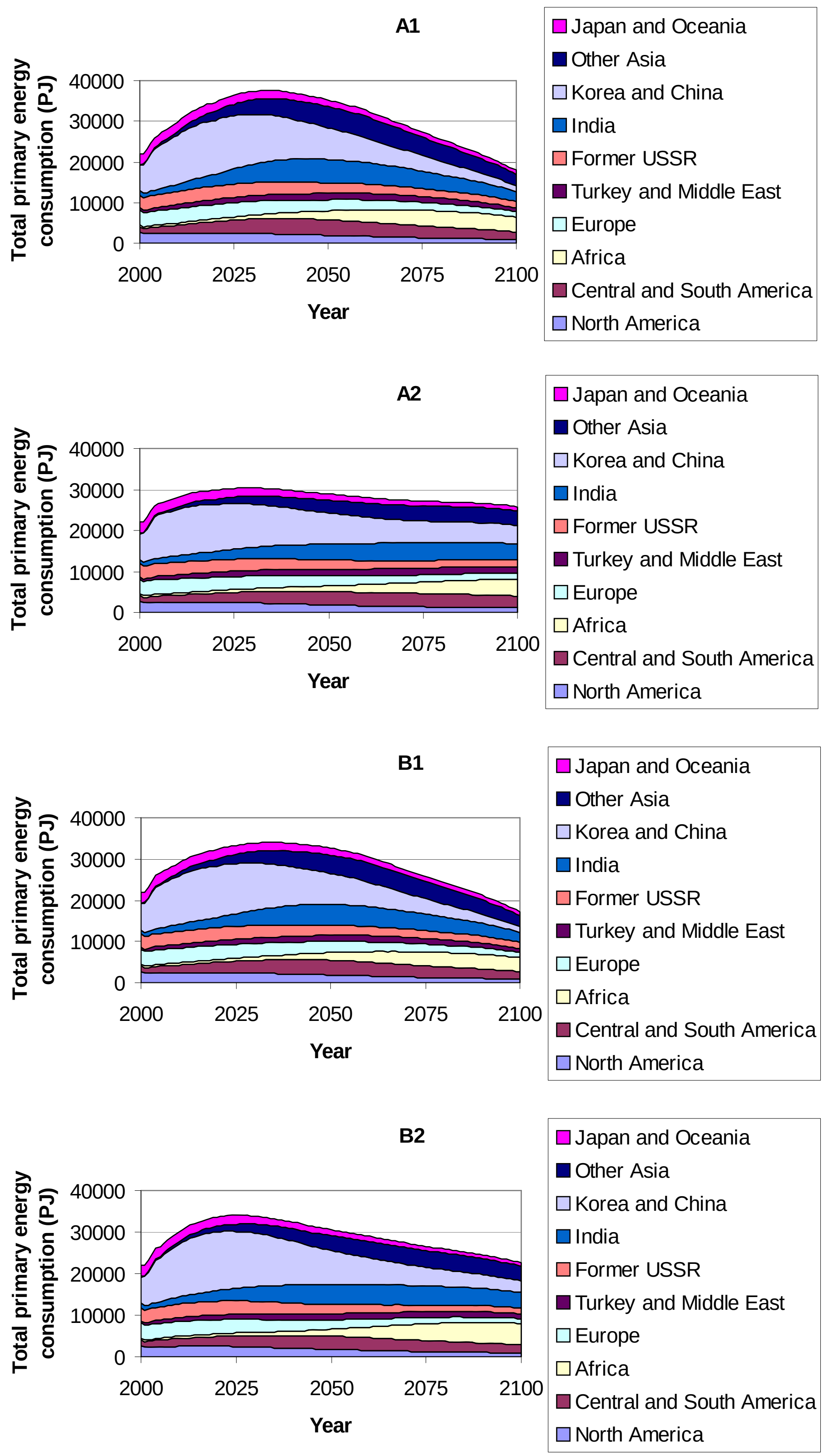


Figure 7-13 World total primary energy use under the four demographic and economic scenarios

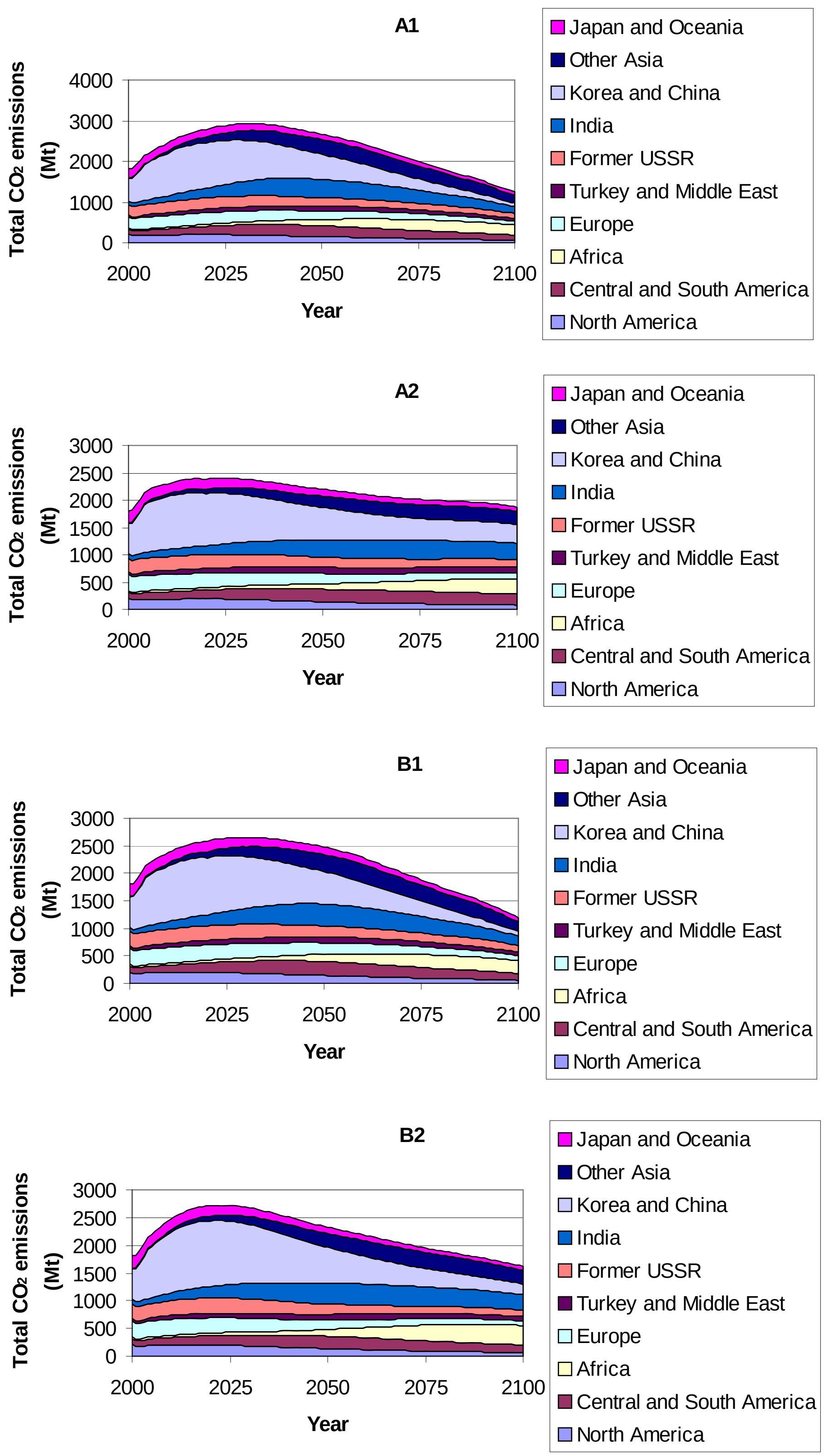


Figure 7-14 World total CO_2 emissions under the four demographic and economic scenarios

As a result of an increasing share of the electric arc furnace in total steel production, the share of electricity use also increases over time. We show in Figure 7-15, the share of fuel and electricity use in the B2 scenario as an example.

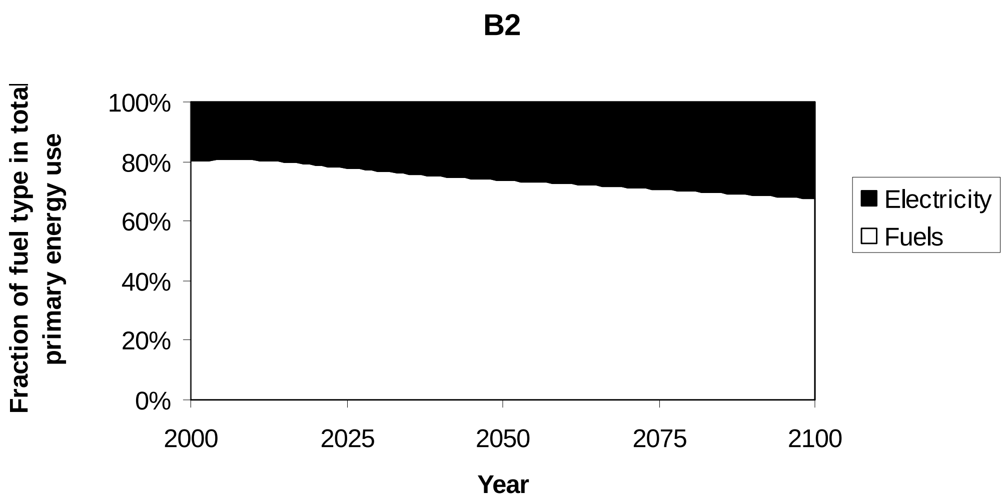


Figure 7-15 Share of fuels and electricity use in total primary energy consumption

Table 7-3 Comparison of total worldwide CO_2 emissions from fuel use in Mt between the IPTS and our model.

Region	TIMER region[1]	2003 Our model	2030 IPTS	2030 Our model A1	2030 Our model A2	2030 Our model B1	2030 Our model B2
Africa and Middle East	7-10, 26	42	40	91	80	80	76
China	20	639	360	824	695	758	867
Economies in transition	12, 14-16	294	220	303	263	286	290
EFTA and Turkey	13	17	*20*	39	42	38	37
EU-15	11	184	*145*	160	144	156	144
India	18	86	70	308	188	249	238
Latin America	3-6	99	55	203	158	177	158
North America	1,2	142	130	152	145	149	147
Pacific OECD	23,24	196	110	149	139	147	135
Rest of Asia	21,22,25	8	*45*	174	91	135	107
South Korea	19	58	*45*	48	44	46	49
World		1765	1240	2451	1988	2220	2249

[1] The comparison for EU-15, EFTA and Turkey, Rest of Asia and South Korea is not fully valid. EFTA countries are in our model included in Western Europe. Korea in our model also included North Korea, whereas it is included in the Rest of Asia in the IPTS model. Incomparable data are given in italics.

7.5 The results in perspective, sensitivity and alternative model assumptions

7.5.1 Material efficiency, energy efficiency and obsolete scrap recovery rate

In this section, we assess the sensitivity of the key model outcomes (i.e. steel consumption, energy use, share of secondary inputs and primary energy use and CO_2 emissions) to some of the exogenous model parameters. We test the sensitivity to six different model assumptions (Table 7-4):

1. A material efficiency factor of 0% per year instead of 0.65% per year.
2. A material efficiency factor of 1% per year instead of 0.65% per year.
3. From 1980 onwards, frozen energy efficiency levels
4. From 1990, only best practice plants installed
5. From 2003 onwards, constant worldwide technology shares
6. From 2020 onwards, 50% instead of 70% of available obsolete scrap recovered
7. From 2020 onwards, 100% of available obsolete scrap recovered

1 and 2

The material efficiency factor results in a declining intensity of use over time (compare Figure 3-8 with Figure 7-5). Assuming no material efficiency improvement over time[22] results in average worldwide per capita steel consumption figures that are in 2050 40% higher compared to the baseline scenario and in 2100 even 100% higher. As a result, the total apparent crude steel consumption in 2100 would be 3579 to 4728 Mt (depending on the scenario), which is in the same order as the 3900 Mt project in the VLEEM model, where also no material efficiency improvement is assumed. As a result of the higher consumption and production levels, a smaller part of steel can be produced from secondary inputs and the primary energy use and CO_2 emissions therefore increase by somewhat higher percentages than the consumptions levels. If we assume an efficiency improvement of 1% per year rather than the 0.65% in our baseline, steel consumption levels in 2050 are 15% and in 2100 30% lower compared with our baseline. The fraction of secondary inputs is in this case somewhat higher and the drop in primary energy use and CO_2 is therefore a little higher than the drop in consumption levels.

3 and 4

If we freeze energy efficiency levels to 1980 levels, worldwide primary energy use and CO_2 emissions are 50% (2050) and 90% (2100) higher than using our baseline assumption, showing the major impact of efficiency improvements on energy use and CO_2 If we assume all plants after 1990 to be installed using best practice technologies, primary energy use and CO_2 emission are approximately 10% lower in 2050[23]. Using best practice technologies from 1990 onwards yields a total primary energy use of 2300 – 2800 in 2030, which is in the same

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[22] As explained in Section 3.4.1, our assumptions with respect to the development of the circulating and prompt scrap ratio already implies an efficiency improvement of approximately 0.15% per year. The 0% efficiency improvement assumed in this sensitivity analysis can therefore really be regarded as a lower limit.

[23] The relative small difference results from the fact that also in our baseline assumption, energy efficiency levels are assumed to converge to best practice levels in 2050. The results in the baseline are still somewhat higher. This is because the installed capacity in 2050 was build in the years before 2050 with EEI levels above the best practice level (Table 5-6). In 2100, the results for the baseline and for the alternative scenario are the same because the development of the EEI is the same between 2050 and 2100 in the baseline and alternative scenario.

range as the IPTS model if we correct for the different production levels[24]. This confirms the more rapid diffusion of more efficient technologies in the IPTS model compared to our assumptions on energy efficiency improvements over time.

5

If we assume technology shares to remain constant to worldwide 2003 levels, primary energy use in 2050 is 10% and in 2100 18-35% higher compared to the default case where the share of scrap-based steel is expected to increase (Figure 7-7) in the future. The CO_2 emissions are 18-19% (2050) and 33-59% (2100) higher. This results from the fact that the increased share of scrap based electric arc furnaces in the default case induces a shift from fuels to electricity. In our simple way of calculating primary energy use and CO_2 emissions, electricity has a lower emission factor in primary terms compared to fuel use and as result, the effect of frozen technology shares on CO_2 emission is larger than the effect on primary energy use.

6 and 7

In our model, we assume 70% recovery of obsolete scrap. The sensitivity analysis shows that complete recovery of obsolete scrap can lead to a drop in primary energy use and CO_2 emissions of 20-30% in 2100 as a result of a higher share of secondary inputs[25]. If, on the other hand, we assume a recovery rate of 50% rather than 70%, primary energy use and CO_2 emissions in 2100 increases by approximately 15-30% compared to our baseline assumption.

[24] Crude steel production our model in our model is 1.22 – 1.33 times higher than in the IPTS model (Table 7-2). The total primary energy use using best practice levels since 1990 is 1.25 – 1.40 times higher than according to the IPTS model.

[25] Scrap based electric arc furnaces get a larger share and the share of electricity is therefore also larger. Since electricity has in our simple model a lower emission factor in primary terms, the drop in CO_2 emissions is larger.

Table 7-4 Sensitivity of model outcomes to key model parameters

	2050								2100							
Baseline	A1	Change	A2	Change	B1	Change	B2	Change	A1	Change	A2	Change	B1	Change	B2	Change
Apparent crude steel consumption (Mt)	2403		1989		2227		2107		1991		2523		1902		2309	
Apparent crude steel consumption per capita (t / capita)	0.29		0.19		0.27		0.23		0.29		0.20		0.28		0.25	
Share of secondary inputs (%)	52%		52%		52%		53%		71%		60%		71%		63%	
Worldwide total primary energy use (PJ)	35236		28918		32588		30579		17938		25770		17258		22697	
Worldwide total CO2 emissions (Mt)	2669		2197		2473		2325		1242		1876		1200		1618	
Material efficiency factor 0%																
Apparent crude steel consumption (Mt)	3260	136%	2688	135%	3018	136%	2849	135%	3749	188%	4728	187%	3579	188%	4343	188%
Apparent crude steel consumption per capita (t / capita)	0.40	136%	0.26	135%	0.37	136%	0.32	135%	0.54	188%	0.38	187%	0.52	188%	0.47	188%
Share of secondary inputs (%)	48%	93%	49%	93%	48%	93%	49%	93%	63%	88%	53%	89%	62%	88%	56%	88%
Worldwide total primary energy use (PJ)	49132	139%	40225	139%	45410	139%	42620	139%	37193	207%	51636	200%	35733	207%	46130	203%
Worldwide total CO2 emissions (Mt)	3755	141%	3085	140%	3478	141%	3274	141%	2656	214%	3832	204%	2561	213%	3368	208%
Material efficiency factor 1%																
Apparent crude steel consumption (Mt)	2038	85%	1691	85%	1890	85%	1790	85%	1414	71%	1799	71%	1351	71%	1640	71%
Apparent crude steel consumption per capita (t / capita)	0.25	85%	0.16	85%	0.23	85%	0.20	85%	0.21	71%	0.14	71%	0.20	71%	0.18	71%
Share of secondary inputs (%)	54%	104%	55%	104%	54%	104%	55%	104%	75%	105%	64%	108%	74%	105%	68%	108%
Worldwide total primary energy use (PJ)	29354	83%	24134	83%	27161	83%	25486	83%	12239	68%	17505	68%	11803	68%	15232	67%
Worldwide total CO2 emissions (Mt)	2210	83%	1823	83%	2050	83%	1926	83%	840	68%	1257	67%	815	68%	1066	66%
Frozen EEI																
Worldwide total primary energy use (PJ)	52234	148%	43067	149%	48379	148%	45768	150%	33904	189%	50277	195%	32642	189%	43823	193%
Worldwide total CO2 emissions (Mt)	3959	148%	3277	149%	3675	149%	3484	150%	2339	188%	3669	196%	2262	188%	3125	193%
BP EEI from 1990 onwards																
Worldwide total primary energy use (PJ)	31230	89%	25689	89%	28937	89%	27083	89%	17954	100%	25787	100%	17274	100%	22714	100%
Worldwide total CO2 emissions (Mt)	2361	88%	1949	89%	2193	89%	2056	88%	1243	100%	1878	100%	1201	100%	1619	100%
Constant technology shares																
Worldwide total primary energy use (PJ)	38381	109%	31706	110%	35500	109%	33689	110%	24184	135%	30509	118%	23093	134%	27949	123%
Worldwide total CO2 emissions (Mt)	3141	118%	2595	118%	2906	117%	2757	119%	1979	159%	2497	133%	1890	158%	2287	141%
Obsscrap recovery rate 50%																
Share of secondary inputs (%)	42%	81%	42%	81%	42%	81%	43%	81%	55%	77%	46%	78%	54%	77%	49%	77%
Worldwide total primary energy use (PJ)	38576	109%	31743	110%	35684	110%	33635	110%	21495	120%	29454	114%	20634	120%	26320	116%
Worldwide total CO2 emissions (Mt)	3005	113%	2484	113%	2786	113%	2637	113%	1586	128%	2236	119%	1527	127%	1971	122%
Obsscrap recovery rate 100%																
Share of secondary inputs (%)	66%	128%	67%	129%	66%	128%	68%	129%	89%	124%	80%	133%	88%	124%	82%	129%
Worldwide total primary energy use (PJ)	30219	86%	24674	85%	27931	86%	25983	85%	14187	79%	20297	79%	13754	80%	18122	80%
Worldwide total CO2 emissions (Mt)	2163	81%	1767	80%	2003	81%	1856	80%	886	71%	1342	72%	867	72%	1180	73%

7.5.2 Trade

In the default trade assumption, we freeze absolute trade to 2003 levels (Section 7.3.1), but in the model, also two alternative trade scenarios are included as discussed in Section 4.4.1:

- Trade assumption 2; no steel trade; steel consumption equals steel production
- Trade assumption 3; region-specific relative steel trade

On the worldwide level, the trade assumptions have very little effect on the energy and CO_2 emission projection in the longer term (Table 7-5). This results from the fact that total worldwide consumption remains unchanged in the three trade scenarios. The small differences are caused by the differences in regional energy efficiency levels (only for 2050, because in 2100 all regions are assumed to have the same efficiency levels) and by differences in the share of direct reduced iron versus pig iron production. On the regional level, the differences between the three trade scenarios can, however, be substantial. In Appendix 8, we give an overview of the regional production using trade assumption 2 and 3 and highlight those regions where the difference in production compared to the default trade assumption is larger than 25%. The second assumption (no trade) results in substantially (defined as here as more than +/- 25%) different production levels in 2050 and 2100 for the four regions (South Africa, Ukraine+, Russia+ and Japan) that have large net export levels in 2050 and 2100 in the default trade scenario (Appendix 7), whereas they have no net export in trade scenario 2. In the third trade assumption, region-specific assumptions are made about the development of net trade. Currently low developed regions having a net import of steel (3,4,6,7,8,9,17,18,20,21,22,25 and 26) are assumed to reach a net import level of 0% at a per capita income of 10,000 1995 ppp $, whereas constant net import (in absolute terms) is assumed in the default trade scenario. Depending on the current relative net import levels and on the development trajectory, this results in either higher or lower production levels compared to the default trade assumption in future years. Differences with the default trade assumption can be substantial as the results for e.g. Western and Eastern Africa in 2050 show, but by default, they become smaller with increasing income, because the constant absolute net import assumed in the default scenario results in very low relative net import when consumption starts to increase, an effect which is also simulated by the third trade scenario. As a result, the production levels for many of these regions in 2100 are very comparable for both trade assumptions in 2100. Exceptions are the Western and Eastern African regions in the A2 scenario. In this scenario, both regions still have quite low income levels in 2100, resulting in a substantial relative net import and therefore, lower production levels using the third trade assumption compared to the default assumption where the increased consumption already results in very low relative net import. The relative net export of the former centrally planned regions (12, 14, 15 and 16) is assumed to decline to 0% in the coming decades and therefore, results for these regions are identical using the second and third trade assumption. For Russia+ and Ukraine+, this results in quite different production levels compared to the default trade scenario, where these regions maintain an exporting position. The overall absolute trade needs to be balanced and in the third assumption, we accomplish this by varying the relative net export of the currently exporting regions (Western Europe, Japan, Brazil and South Africa), resulting in quite different production levels for some of those regions (e.g. South Africa).

We would like to emphasise once more that none of the trade assumption is based on any sound and consistent economic or other theory. The differences in trade assumptions on the regional results of the model can be substantial as the analyses in this Section show and it is important to realise this, especially when using regional results of the model. It is obvious that the trade section of the model can be substantially improved and that more alternative trade assumptions (e.g. scenario specific ones) could be included. Suggestions for improvements of the trade section are given in the next chapter.

Table 7-5 Sensitivity of trade scenarios on worldwide energy use and CO_2 emissions

	2050								2100							
Baseline	A1	Change	A2	Change	B1	Change	B2	Change	A1	Change	A2	Change	B1	Change	B2	Change
Worldwide total primary energy use (PJ)	35236		28918		32588		30579		17938		25770		17258		22697	
Worldwide total CO2 emissions (Mt)	2669		2197		2473		2325		1242		1876		1200		1618	
Scenario 2, no trade	A1	Change	A2	Change	B1	Change	B2	Change	A1	Change	A2	Change	B1	Change	B2	Change
Worldwide total primary energy use (PJ)	35239	100%	28907	100%	32586	100%	30575	100%	17756	99%	25686	100%	17098	99%	22613	100%
Worldwide total CO2 emissions (Mt)	2641	99%	2168	99%	2445	99%	2297	99%	1201	97%	1847	98%	1162	97%	1588	98%
Scenario 3, region-specific relative trade	A1	Change	A2	Change	B1	Change	B2	Change	A1	Change	A2	Change	B1	Change	B2	Change
Worldwide total primary energy use (PJ)	35195	100%	28861	100%	32540	100%	30497	100%	17757	99%	25751	100%	17100	99%	22618	100%
Worldwide total CO2 emissions (Mt)	2649	99%	2175	99%	2450	99%	2300	99%	1202	97%	1876	100%	1162	97%	1589	98%

7.5.3 Other variables

Also other input variables can of course be varied, e.g. the shares of various product groups in total crude steel consumption and the assumed lifetime distributions assumed for these product groups. However, the few examples given above already show the major impact of the model assumptions on the final results and give some idea about the typical sensitivity of basic model assumptions on the final model results. This, in turn, demonstrates the large uncertainties associated with this kind of model projections and make clear that the model results should always be interpreted having these basic model assumptions in mind. There are various possibilities to improve the modelling framework presented in this study and to extend the model also to other materials. In the next Chapter, we summarise possible direction for future improvements and extensions.

8 Recommendations for model improvements and future research

8.1 Introduction

The model developed in this study leave room for improvements in various directions. In this chapter, we give some of these directions for possible improvements, but we also broaden the scope and summarise on a more conceptual level directions for future research on material demand modelling.

8.2 The link to the TIMER model and beyond

The steel model developed in this study can be classified as a bottom-up model in which the drivers for material demand are exogenous macro-economic and demographic inputs (GDP and population). All the models discussed in Appendix 2 as well as the TIMER model itself are of this bottom-up type. In an overview paper on material efficiency in energy demand modelling, Nathani and Jochem (2004) give an overview of bottom-up modelling approaches for studying energy systems and GHG emissions and the position of material use and material efficiency in these models. They distinguish optimisation models, the partial equilibrium model STREAM and a more general group of simulation models of material and energy use.

In optimisation models (such as the MARKAL family of models including the models by Gielen discussed in Appendix 2) a set of current and future technical options is described with detailed data on costs and material and energy inputs and outputs. Using certain exogenously defined demand levels, the least-cost combination of technologies is found to fulfil the defined demand level. Least-cost optimisation is used by various models mentioned in Appendix 2 to model steel trade and steel production by technology (see Section 4.1.2). In the partial equilibrium model STREAM (also mentioned in Appendix 2), supply and demand on the raw material, the primary and the secondary material market is balanced, using exogenous material demand functions. The rather broad group of simulation models includes all kind of models used to analyse energy and material flows at various levels of regional and industrial aggregation.

Contrary to bottom-up models, top-down models describe the total (macro)-economic system. Nathani and Jochem distinguish macro-econometric, computable general equilibrium models and econometric input-output models. The outputs of these top-down economic models are in their turn often used as inputs into the bottom-up models. The general equilibrium WorldScan model developed by the Central Planning Bureau in the Netherlands is, for example, used to generate inputs for the TIMER model. Also the Markal model is sometimes linked to a macro-economic model.

It can be concluded that *'top-down model are too highly aggregated to catch material specifics and bottom-up models generally lack the integration into the national economy'* (Nathani, 2005). Therefore, there is a need for hybrid models that combine the detail of bottom-up modelling with the economy-wide characteristics of top-down models.

Nathani and Jochem (2004) distinguish two groups of these kinds of hybrid models. In the first group, a detailed bottom-up model is sequentially linked to an economic model, but there is no feedback from the material model back to the economic model. In the second group, feedback links are present and both models are fully linked and interdependent. Examples of these kinds of models are quite rare and Nathani and Jochem recommend further development of these kinds of hybrid models.

If we would like to couple our model to the TIMER model, we are challenged with a similar problem of coupling a detailed bottom-up model to a more top-down model. Ideally, one would like to let the steel model (and a later stage, models for other materials) be an integral part of the TIMER model[26]. Since the key exogenous drivers of the TIMER model and our model (i.e. income and population development) are the same, this would in principle be possible. However, a full re-calibration of the TIMER model should in that case be performed to separate energy use and value added resulting form iron and steel production from the energy use and value added of the remainder of the industrial sector. As a first, step, the contribution of the iron and steel sector and the contribution of two other main materials (paper and cement) to the total value added and the total energy use of the industrial sector will be studied in a follow-up project to the current study (Roorda, 2006).

8.3 Steel demand

In our model, steel consumption is modelled using the intensity of use hypothesis. Although this method is quite well accepted in long-term demand modelling, it remains unsatisfactory in the sense that it provides little explanatory power to the observed apparent crude steel consumption curves. One can think of several directions to improve the understanding of steel demand:

- Detailed historical analyses of steel and other material demand at the level of final consumer categories to better understand which developments in the past (material substitution, material efficiency improvements, changes in economic structure) have led to the observed steel and other material consumption behaviour. The studies by Roberts (1990) and Crompton (2000) on the contribution of material composition of products (i.e. the amount of steel used per economic output of a certain sector and the production composition of income (i.e. the contribution of certain sectors to total GDP) are interesting examples of such detailed analyses. An additional advantage is that they provide a coupling between the physical world and the economic output of sectors, which can be coupled to the macro-economy, e.g. via input-output analyses. Countries with a good data situation with respect to economic and physical data (e.g. Japan and the US) might offer the best opportunity for such detailed analyses for long time-series. In the EPIST project (Lysen, 2006), also an attempt was made to understand the relationship between physical and monitory growth. Not only basic materials, but also other sectors such as households and transport were studied. The analyses for materials provide interesting insights, but they also show large uncertainties due to incompatible system boundaries and low data quality. They therefore call for further analyses of the same type but using more reliable data and for detailed material flow analyses across applications and as a function of time.
- Cross country comparisons to better understand the differences of steel demand between currently developing countries and developed countries. The intensity of use hypothesis implies that developing countries have a large steel demand for infrastructure. It would be interesting to show this also based on available statistics on steel demand per product category (e.g. using input-output data for various countries such as the GTAP database). If the steel demand per product category is better understood, varying product shares over time can be used also in our model rather than the fixed shares currently used in our model (see also next bullet point and next section)
- An interesting direction along the same line is to project steel demand based on an assumed development of the steel stock in use per product category. Although it shifts in a way the problem from projecting steel demand directly as function of exogenous variables to projecting the steel stock as function of exogenous inputs, it offers opportunities to couple the steel demand more directly to one of the main

[26] A further step could be to couple the TIMER model directly to a macro-economic model.

arguments always used to explain the inverse U behaviour of the intensity of use curve (i.e. the necessity of building up a stock of infrastructure at the beginning of a region's development). An attempt to use steel stocks as a tool for steel demand projection is given by Mueller (2005) for China. Using the hypothesis that the steel stock for various product groups saturates at a certain per capita income, he projects steel demand for those categories. As a result, the share of construction steel in steel demand for China is expected to drop significantly after 2040[27]. It would be very interesting to further explore and test the hypothesis by Mueller with historical analysis of steel stocks and resulting steel demand by product categories for more countries[28].

8.4 Steel production by technology and trade flows

8.4.1 Trade flows based on differences in costs

A valuable addition to the model would be to include production cost based trade modelling at least as one of the trade scenario options. Detailed data on production costs and the relative contribution of cost factors (energy, materials, labour, capital) on these costs are difficult to find and not always consistent as becomes clear from Table 8-1, where two examples are given from the STREAM model (Elzenga et al., 2001) and from Daniels (2002) respectively.

Table 8-1 Share (in %) of capital, labour, energy, material and other costs in total

	Capital	Labour	Energy	Materials
Stream				
Primary	54	26	14	6
Secondary	50	27	13	10
Daniels[1]				
BF	53	20	17	11
DR: Midrex	52	15	22	11
EAF	38	13	10	39

[1] In the study by Daniels, a large fraction of the costs are allocated to Operation and Maintenance costs. In this table, we added those to the capital costs.

The data from the STREAM model are rather unlikely given the fact that share of energy use in the primary steel production can be expected to be much higher compared to secondary steel production and the share of material costs much lower (iron ore is much cheaper compared to scrap). Based on these two examples we conclude that it will require a substantial effort to develop a consistent and complete database with production cost functions at a regional level from open literature sources that can be used to derive trade flows, including also transportation costs and trade barriers, even if a relatively high level of aggregation as used in the two studies mentioned above[29]. Provided that the data is available it is relatively easy to implement cost-based trade into the model[30].

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[27] Mueller projects a stabilising stock in China around 2040 for all steel products. Products with a relatively short life time (cars etc.) are replaced continuously and demand remains high to keep the stock at the stabilisation level. Products with a long lifetime on the other hand, only need replacement after a long time period and as a result, demand for steel in these product categories (infrastructure) drops.

[28] Mueller for examples shows a saturation of the steel stock in use per capita in the US from 1980 onwards based on historical data. A study using a similar method for the UK (Ley et al., 2002) on the other hand, shows a construction steel stock in the UK that still increases rapidly.

[29] The current version of the TIMER model already includes some of the information required (e.g. labour costs and transportation costs).

[30] In the TIMER model, a so-called multinomial logit function is normally used to split a certain demand into shares based on the difference of a certain variable (e.g. costs per technology or region). A parameter labda determines to which extent the difference in the variable (e.g. costs) drive the split (i.e.

8.4.2 Improvements to the material flow model

To further improve the material flow model it is recommended to conduct more detailed regional case studies to validate the outcomes of the current model and to improve input parameters. Elements that should get attention in such a detailed analysis could be:

- The development of product shares in the total steel consumption over time
- The influence of indirect trade flows on the total stock in use (e.g. for a country like Korea) and a possible inclusion of these indirect trade flows into the model.
- Circulating and prompt scrap ratios for various product groups and recovery rates for circulating and prompt scrap[31].
- More detailed analysis about the average lifetime of steel products, for example based on demolition rates for build infrastructure etc.
- The fate of non-recycled steel (e.g. re-use, landfill, oxidation etc.). Information could be gathered based on interviews with experts within the industry.

An obvious barrier to such detailed analysis is the limited data availability, especially for historical data, which are necessary given the long lifetime of the products involved.

8.5 Energy use and CO_2 emissions

Comparable to steel trade, it is also possible to let the share of various steel production technologies be driven by production cost differences between technologies. The supply of steel scrap (as modelled) could be used to determine a steel scrap price curve[32]. In such a model, also CO_2 capture and storage could be implemented as function of certain CO_2 price levels. Gielen and Podkanski (2006) project a CO_2 emission reduction potential of 300-500 Mt CO_2 from carbon capture and storage by 2050. A wide variety of different steel production technologies can be distinguished. In a recent article in Metal Bulletin Monthly, 36 present and radically new steel processes in terms of CO_2 emissions and energy consumption are given which are studied in the Ultra-low CO_2 Steelmaking (ULCOS) project (Metal Bulletin Monthly, 2005). Although the current model allows the calculation of primary energy use and CO_2 emissions in a reasonable way using a clear set of basic assumptions, it is obvious that more sophisticated and more detailed scenario could be explored if more technologies would be included in the model.

8.6 Extension with other materials

The modelling framework presented in this study can easily be used to study also other energy-intensive and other materials such as paper, cement, aluminium and petrochemicals. Such an effort could result in model that covers a very large part of the energy use of the manufacturing industry. Depending on the material studied, the material flow approach can yield interesting insights in e.g. the stock of certain materials (cement, plastics) in relation to economic development, for example by comparison with the stock turn-over of the built environment. Such a tool in which various materials are included could then in principle also be used to study material substitution effects and could be used as a very flexible tool to explore future scenarios of the materials industry.

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a labda of 0 results in an equal division regardless of costs and a high labda yields a 100% share of the cheapest option).

[31] We currently assume 100% recovery of circulating and prompt scrap. The recovery rate for some regions might be lower.

[32] One could for example let the scrap price vary with the obsolete scrap recovery rate.

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Appendix 1 List of 26 TIMER regions

Nr.	TIMER region	Country
1	Canada	CANADA
2	USA	SAINT PIERRE AND MIQUELON
2	USA	UNITED STATES
2	USA	UNITED STATES MINOR OUTLYING ISLANDS
3	Mexico	MEXICO
4	Rest Central America	ANGUILLA
4	Rest Central America	ANTIGUA AND BARBUDA
4	Rest Central America	ARUBA
4	Rest Central America	BAHAMAS
4	Rest Central America	BARBADOS
4	Rest Central America	BELIZE
4	Rest Central America	BERMUDA
4	Rest Central America	CAYMAN ISLANDS
4	Rest Central America	COSTA RICA
4	Rest Central America	CUBA
4	Rest Central America	DOMINICA
4	Rest Central America	DOMINICAN REPUBLIC
4	Rest Central America	EL SALVADOR
4	Rest Central America	GRENADA
4	Rest Central America	GUADELOUPE
4	Rest Central America	GUATEMALA
4	Rest Central America	HAITI
4	Rest Central America	HONDURAS
4	Rest Central America	JAMAICA
4	Rest Central America	MARTINIQUE
4	Rest Central America	MONTSERRAT
4	Rest Central America	NETHERLANDS ANTILLES
4	Rest Central America	NICARAGUA
4	Rest Central America	PANAMA
4	Rest Central America	PUERTO RICO
4	Rest Central America	SAINT KITTS AND NEVIS
4	Rest Central America	SAINT LUCIA
4	Rest Central America	SAINT VINCENT AND THE GRENADINES
4	Rest Central America	TRINIDAD AND TOBAGO
4	Rest Central America	TURKS AND CAICOS ISLANDS
4	Rest Central America	VIRGIN ISLANDS, BRITISH
4	Rest Central America	VIRGIN ISLANDS, U.S.
5	Brazil	BRAZIL
6	Rest South America	ARGENTINA
6	Rest South America	BOLIVIA
6	Rest South America	BOUVET ISLAND
6	Rest South America	CHILE
6	Rest South America	COLOMBIA
6	Rest South America	ECUADOR
6	Rest South America	FALKLANDS ISLANDS (MALVINAS)
6	Rest South America	FRENCH GUIANA
6	Rest South America	GUYANA
6	Rest South America	PARAGUAY
6	Rest South America	PERU
6	Rest South America	SOUTH GEORGIA AND THE SOUTH SANDWICH ISLANDS
6	Rest South America	SURINAME
6	Rest South America	URUGUAY

6	Rest South America	VENEZUELA
7	Northern Africa	ALGERIA
7	Northern Africa	EGYPT
7	Northern Africa	LIBYAN ARAB JAMAHIRIYA
7	Northern Africa	MOROCCO
7	Northern Africa	TUNISIA
7	Northern Africa	WESTERN SAHARA
8	Western Africa	BENIN
8	Western Africa	BURKINA FASO
8	Western Africa	CAMEROON
8	Western Africa	CAPE VERDE
8	Western Africa	CENTRAL AFRICAN REPUBLIC
8	Western Africa	CHAD
8	Western Africa	CONGO
8	Western Africa	CONGO, THE DEMOCRATIC REPUBLIC OF THE
8	Western Africa	CÔTE D'IVOIRE
8	Western Africa	EQUATORIAL GUINEA
8	Western Africa	GABON
8	Western Africa	GAMBIA
8	Western Africa	GHANA
8	Western Africa	GUINEA
8	Western Africa	GUINEA-BISSAU
8	Western Africa	LIBERIA
8	Western Africa	MALI
8	Western Africa	MAURITANIA
8	Western Africa	NIGER
8	Western Africa	NIGERIA
8	Western Africa	SAINT HELENA
8	Western Africa	SAO TOME AND PRINCIPE
8	Western Africa	SENEGAL
8	Western Africa	SIERRA LEONE
8	Western Africa	TOGO
9	Eastern Africa	BURUNDI
9	Eastern Africa	COMOROS
9	Eastern Africa	DJIBOUTI
9	Eastern Africa	ERITREA
9	Eastern Africa	ETHIOPIA
9	Eastern Africa	KENYA
9	Eastern Africa	MADAGASCAR
9	Eastern Africa	MAURITIUS
9	Eastern Africa	MAYOTTE
9	Eastern Africa	RÉUNION
9	Eastern Africa	RWANDA
9	Eastern Africa	SEYCHELLES
9	Eastern Africa	SOMALIA
9	Eastern Africa	SUDAN
9	Eastern Africa	UGANDA
10	South Africa	SOUTH AFRICA
11	Western Europe	ANDORRA
11	Western Europe	AUSTRIA
11	Western Europe	BELGIUM
11	Western Europe	DENMARK
11	Western Europe	FAROE ISLANDS
11	Western Europe	FINLAND
11	Western Europe	FRANCE
11	Western Europe	GERMANY
11	Western Europe	GIBRALTAR

11	Western Europe	GREECE
11	Western Europe	HOLY SEE (VATICAN CITY STATE)
11	Western Europe	ICELAND
11	Western Europe	IRELAND
11	Western Europe	ITALY
11	Western Europe	LIECHTENSTEIN
11	Western Europe	LUXEMBOURG
11	Western Europe	MONACO
11	Western Europe	NETHERLANDS
11	Western Europe	NORWAY
11	Western Europe	PORTUGAL
11	Western Europe	SAN MARINO
11	Western Europe	SPAIN
11	Western Europe	SVALBARD AND JAN MAYEN
11	Western Europe	SWEDEN
11	Western Europe	SWITZERLAND
11	Western Europe	UNITED KINGDOM
12	Central Europe	ALBANIA
12	Central Europe	BOSNIA AND HERZEGOVINA
12	Central Europe	BULGARIA
12	Central Europe	CROATIA
12	Central Europe	CYPRUS
12	Central Europe	CZECH REPUBLIC
12	Central Europe	ESTONIA
12	Central Europe	HUNGARY
12	Central Europe	LATVIA
12	Central Europe	LITHUANIA
12	Central Europe	MACEDONIA, THE FORMER YUGOSLAV REPUBLIC OF
12	Central Europe	MALTA
12	Central Europe	POLAND
12	Central Europe	ROMANIA
12	Central Europe	SLOVAKIA
12	Central Europe	SLOVENIA
12	Central Europe	YUGOSLAVIA
13	Turkey	TURKEY
14	Ukraine +	BELARUS
14	Ukraine +	MOLDOVA, REPUBLIC OF
14	Ukraine +	UKRAINE
15	Asia-Stan	KAZAKSTAN
15	Asia-Stan	KYRGYZSTAN
15	Asia-Stan	TAJIKISTAN
15	Asia-Stan	TURKMENISTAN
15	Asia-Stan	UZBEKISTAN
16	Russia +	ARMENIA
16	Russia +	AZERBAIJAN
16	Russia +	GEORGIA
16	Russia +	RUSSIAN FEDERATION
17	Middle East	BAHRAIN
17	Middle East	IRAN, ISLAMIC REPUBLIC OF
17	Middle East	IRAQ
17	Middle East	ISRAEL
17	Middle East	JORDAN
17	Middle East	KUWAIT
17	Middle East	LEBANON
17	Middle East	OMAN
17	Middle East	QATAR
17	Middle East	SAUDI ARABIA

17	Middle East	SYRIAN ARAB REPUBLIC
17	Middle East	UNITED ARAB EMIRATES
17	Middle East	YEMEN
18	India	INDIA
19	Korea	KOREA, DEMOCRATIC PEOPLE'S REPUBLIC OF
19	Korea	KOREA, REPUBLIC OF
20	China +	CHINA
20	China +	HONG KONG
20	China +	MACAU
20	China +	MONGOLIA
20	China +	TAIWAN, PROVINCE OF CHINA
21	Southeastern Asia	BRUNEI DARUSSALAM
21	Southeastern Asia	CAMBODIA
21	Southeastern Asia	EAST TIMOR
21	Southeastern Asia	LAO PEOPLE'S DEMOCRATIC REPUBLIC
21	Southeastern Asia	MALAYSIA
21	Southeastern Asia	MYANMAR
21	Southeastern Asia	PHILIPPINES
21	Southeastern Asia	SINGAPORE
21	Southeastern Asia	THAILAND
21	Southeastern Asia	VIET NAM
22	Indonesia +	INDONESIA
22	Indonesia +	PAPUA NEW GUINEA
23	Japan	JAPAN
24	Oceania	AMERICAN SAMOA
24	Oceania	AUSTRALIA
24	Oceania	CHRISTMAS ISLAND
24	Oceania	COCOS (KEELING) ISLANDS
24	Oceania	COOK ISLANDS
24	Oceania	FIJI
24	Oceania	FRENCH POLYNESIA
24	Oceania	FRENCH SOUTHERN TERRITORIES
24	Oceania	GUAM
24	Oceania	HEARD ISLAND AND MCDONALD ISLANDS
24	Oceania	KIRIBATI
24	Oceania	MARSHALL ISLANDS
24	Oceania	MICRONESIA, FEDERATED STATES OF
24	Oceania	NAURU
24	Oceania	NEW CALEDONIA
24	Oceania	NEW ZEALAND
24	Oceania	NIUE
24	Oceania	NORFOLK ISLAND
24	Oceania	NORTHERN MARIANA ISLANDS
24	Oceania	PALAU
24	Oceania	PITCAIRN
24	Oceania	SAMOA
24	Oceania	SOLOMON ISLANDS
24	Oceania	TOKELAU
24	Oceania	TONGA
24	Oceania	TUVALU
24	Oceania	VANUATU
24	Oceania	WALLIS AND FUTUNA
25	Rest Southern Asia	AFGANISTAN
25	Rest Southern Asia	BANGLADESH
25	Rest Southern Asia	BHUTAN
25	Rest Southern Asia	BRITISH INDIAN OCEAN TERRITORY
25	Rest Southern Asia	MALDIVES

25	Rest Southern Asia	NEPAL
25	Rest Southern Asia	PAKISTAN
25	Rest Southern Asia	SRI LANKA
26	Rest Southern Africa	ANGOLA
26	Rest Southern Africa	BOTSWANA
26	Rest Southern Africa	LESOTHO
26	Rest Southern Africa	MALAWI
26	Rest Southern Africa	MOZAMBIQUE
26	Rest Southern Africa	NAMIBIA
26	Rest Southern Africa	SWAZILAND
26	Rest Southern Africa	TANZANIA, UNITED REPUBLIC OF
26	Rest Southern Africa	ZAMBIA
26	Rest Southern Africa	ZIMBABWE
27	For future use	-

Appendix 2 Overview of existing steel models

Models, including projections

Step		**1 IPTS model** **Projections 1997 – 2030, data 1970 – 1997** **(Hidalgo et al., 2003 and 2005)**	**2 RIVM metals model** **Projections 1990-2100, data 1900 - 1970** **(van Vuuren et al., 1999)**
0-1	Exogenous model inputs	-	-
	Dependent variables	-	-
	Independent variables	-	-
	Aggregation level	-	-
	Remarks	-	-
1-2	Exogenous model inputs	- GDP, Population,	-GDP, Population,
	Dependent variables	- Steel consumption	-Steel Consumption
	'Independent' variables	- GDP, Population, Price (via price elasticity), Time	-GDP, Population, Price (via price elasticity), Time
	Aggregation level	- 38 Regions, 11 Zones	-13 Regions
	Remarks	- IU curves modelled with 3 shape parameters	-IU curve modelled with 3 shape parameters
2-3	Exogenous model inputs	-	-
	Dependent variables	- Steel production	-
	'Independent' variables	- Production costs, capacities	-
	Aggregation level	- 38 Regions, 11 Zones, 7 technologies	-Worldwide
	Remarks	- Correction applied for worldwide difference between consumption and production - Production per region based on regional production costs	-Worldwide demand = Worldwide production
3-4	Exogenous model inputs	- Fuel prices (POLES model), raw materials prices, income	-Energy price
	Dependent variables	- Production by technology	-Production by technology
	'Independent' variables	- Production costs, capacity constraints	-Production costs, capacity constraints
	Aggregation level	- 38 Regions, 11 Zones, 7 technologies	-Worldwide, 2 technologies
	Remarks	- Capacity planning per technology based on expected production and long-term production costs - Production per technology based on short-term production costs - Production costs are sum of variable (O&M, energy, raw materials) and capital costs. - Developments in investment costs based on learning curve	-Production costs are sum of variable (energy, exploration) and capital costs -Developments in capital costs based on learning and ore grade decline
4-6	Exogenous model inputs	- Fixed SEC values for new technologies in 2000, 2010, 2020, 2030?	- Thermodynamic minimum
	Dependent variables	- Demand for energy	- Demand for energy
	'Independent' variables	- Production by technology	- Production by technology
	Aggregation level	- 38 Regions, 11 Zones, 7 technologies, multiple fuels	- Worldwide
	Remarks	- Complex fuel demand model not yet understood	-

Step		**3 Das and Kandpal** **Projections 1992-2021, data 1970-1992** **(Das and Kandpal, 1998)**	**4 Mark C. Roberts** **Projections 1984-2010, data 1963-1983** **(Roberts, 1990)**
0-1	Exogenous model inputs	-	- GDP, Population, Interest rate (for product composition of income)
	Dependent variables	-	- Consumption of products
	Independent variables	-	- Product composition of income - GDP
	Aggregation level	-	-US, 3 ‘products’ (machinery, transport, infrastructure)
	Remarks	-	
1-2	Exogenous model inputs	- GDP	- Exchange rates (to predict export)
	Dependent variables	- Steel consumption	- Steel consumption
	‘Independent’ variables	- GDP	- Consumption of products - Material composition of product - Net export of products - Time
	Aggregation level	- India	- US, 3 ‘products’ (machinery, transport, infrastructure)
	Remarks	- Simple IU formulation based on regression of period 1970-1992	-
2-3	Exogenous model inputs	-?	-
	Dependent variables	- Steel production	-
	‘Independent’ variables	-?	-
	Aggregation level	-?	-
	Remarks	- Fixed import share, variable export share (pp. 1045, first sentence)?	-
3-4	Exogenous model inputs	- Discount rate	-
	Dependent variables	- Production by technology	-
	‘Independent’ variables	- Production costs	-
	Aggregation level	- India, 6 technologies	-
	Remarks	- Production costs are sum of variable (O&M, energy, raw materials) and capital costs.	-
4-6	Exogenous model inputs	- Fixed SEC values	-
	Dependent variables	- Demand for energy	-
	‘Independent’ variables	- Production by technology	-
	Aggregation level	- India	-
	Remarks	-	-

Step		**5 Paul Crompton** **Projections 1997-2005, data 1980-1997** **(Crompton, 2000)**	**6 Matthias Ruth** **Projections 1990-2020, data** **(Ruth, 1998)**
0-1	Exogenous model inputs	- GDP, Population,	-
	Dependent variables	- 'Consumption of products'	-
	Independent variables	- Product composition of income - GDP	-
	Aggregation level	- Japan, 6 'products' (machinery, electrical machinery, transport equipment, other manufacturing, construction, fabricated metal products)	-
	Remarks	-	-
1-2	Exogenous model inputs	- Investment rate as fraction of GDP	-
	Dependent variables	- Steel consumption	-
	'Independent' variables	- Material composition of product - Net export of products - Investment rate as fraction of GDP	-
	Aggregation level	- Japan, 6 'products' (machinery, electrical machinery, transport equipment, other manufacturing, construction, fabricated metal products)	-
	Remarks	-	- No demand function, only production function
2-3	Exogenous model inputs	-	?
	Dependent variables	-	-Steel production
	'Independent' variables	-	?
	Aggregation level	-	-US
	Remarks	-	- Autoregressive integrated moving average method? - Focus on effects of dematerialisation, not on the process itself
3-4	Exogenous model inputs	-	
	Dependent variables	-	- Production by technology
	'Independent' variables	-	- Cumulative production, production rate
	Aggregation level	-	- US, 3 technologies (BF for iron ore and BOF and EAF for steel)
	Remarks	-	- All variables functions of cumulative production or production rate. - All functions are calibrated using time-series between on average 1960 and 1990
4-6	Exogenous model inputs	-	- Fuel mixes in the energy sectors (from DOE)
	Dependent variables	-	- Demand for energy
	'Independent' variables	-	- Technology mix in total production
	Aggregation level	-	- US, 3 technologies, 6 fuels
	Remarks	-	- SEC functions are functions of either cumulative production or production rate (calibrated with time series between 1960 and 1990) - Influence of metals sectors on the energy sectors included?

Step		**7 Paul Crompton** **Projections 1997-2005, data 1970-1997** **(Crompton, 1999)**	**8 Dongling Chen et al.** **Projections 1989-2000, data 1953-1988** **(Chen et al., 1991)**
0-1	Exogenous model inputs	-	-
	Dependent variables	-	-
	Independent variables	-	-
	Aggregation level	-	-
	Remarks	-	-
1-2	Exogenous model inputs	- GDP?	- GDP?
	Dependent variables	- Steel consumption	- Steel consumption
	'Independent' variables	- GDP, investment expenditure, broad money supply	- GDP, price index, broad money supply, steel consumption, investment expenditure
	Aggregation level	- 5 Countries in south East Asia	- China
	Remarks	- Bayesian vector auto-regression model, using historical correlation between variables to predict the future.	- Bayesian vector auto regression model, using historical correlation between variables to predict the future.
2-3	Exogenous model inputs	-	-
	Dependent variables	-	-
	'Independent' variables	-	-
	Aggregation level	-	-
	Remarks	-	-
3-4	Exogenous model inputs	-	-
	Dependent variables	-	-
	'Independent' variables	-	-
	Aggregation level	-	-
	Remarks	-	-
4-5	Exogenous model inputs	-	-
	Dependent variables	-	-
	'Independent' variables	-	-
	Aggregation level	-	-
	Remarks	-	-

Step		**9 Gielen and Morguchi** **Projections 2000-2030, data 1965-2000** **(Gielen and Moriguchi, 2002)**	**10 Gielen and van Dril** **Projections, 2000-2030, data ????** **(Gielen and van Dril, 1999)**
0-1	Exogenous model inputs	- GDP, Population,	- Consumption of defined product and services demand
	Dependent variables	- 'Consumption of products'	- Consumption of defined product and services demand
	Independent variables	- Product composition of income - GDP	- ? - ?
	Aggregation level	- 11 Regions with focus on Japan, 8 Demand categories	- Western Europe
	Remarks	- Demand categories seem to be mainly used for parameter estimation, no demand categories distinguished for future demand.	-
1-2	Exogenous model inputs	-	-
	Dependent variables	- Steel consumption	- Steel consumption
	'Independent' variables	- Material composition of product - Time	- Composition of product and services
	Aggregation level	- 11 Regions with focus on Japan, 8 Demand categories,	- Western Europe
	Remarks	- Improvement of material composition of product modelled as function of time.	- Substitution effect are characterised by discrete product alternatives (Gielen et al., 1998). These product alternatives represent extremes and substitution is driven by differences in production costs.
2-3	Exogenous model inputs	-	-
	Dependent variables	- Metal production	-
	'Independent' variables	- Production costs	-
	Aggregation level	- Worldwide, 11 Regions with focus on Japan	-
	Remarks	- Production per region based on regional production costs	- Demand is Production?
3-4	Exogenous model inputs	-	-
	Dependent variables	- Production by technology	- Production by technology
	'Independent' variables	- Production costs	- Production costs
	Aggregation level	- 11 Regions with focus on Japan, 75 (sub-) processes	- Western Europe, 6 main steel technologies
	Remarks	- Resource costs, Investment costs, fixed costs and variable costs are distinguished.	- ?
4-6	Exogenous model inputs	-	-
	Dependent variables	- Demand for energy	- Demand for energy
	'Independent' variables	- SEC values for the 75 specified technologies	- SEC values defined for all technologies?
	Aggregation level	- 11 Regions with focus on Japan, 75 (sub-) processes, Energy and CO_2	- Western Europe, 6 main steel technologies, Energy and CO_2
	Remarks	-	-

Step		**11 CPB** **Projections 2000-2020, data 1970-1995** **(Mannaerts, 2000)**	**12 Evans and Walton** **Projections 1996-1999, data 1954-1995** **(Evans and Walton, 1997)**
0-1	Exogenous model inputs	-	-
	Dependent variables	-	-
	Independent variables	-	-
	Aggregation level	-	-
	Remarks	-	-
1-2	Exogenous model inputs	- GDP	
	Dependent variables	- Steel consumption	- Steel consumption
	'Independent' variables	- GDP, Population, Time, Energy Price, Investment ratio, Product Price	- Time
	Aggregation level	- Worldwide	- UK
	Remarks	-	- Detailed analysis of time-series of steel consumption using a variety of statistics techniques
2-3	Exogenous model inputs	-	
	Dependent variables	- Material production	
	'Independent' variables	- Relative cost prices and capacity shares	
	Aggregation level	- Worldwide	
	Remarks	-	
3-4	Exogenous model inputs	-	
	Dependent variables	- Production by technology	
	'Independent' variables	- Relative cost prices	
	Aggregation level	- Worldwide, both primary and secondary	
	Remarks	-	
4-5	Exogenous model inputs	-	
	Dependent variables	-	
	'Independent' variables	-	
	Aggregation level	-	
	Remarks	-	

Step		**13 IISI** **Projections 1970-1985, data 1955-1970** **(IISI, 1972)**	**14 Michaelis and Jackson** **Projections1994-2019, data 1954-1994** **(Michaelis and Jackson, 2000)**
0-1	Exogenous model inputs	-	-
	Dependent variables	-	-
	Independent variables	-	-
	Aggregation level	-	-
	Remarks	-	-
1-2	Exogenous model inputs	- GDP, Population	- GPD
	Dependent variables	- Steel consumption	- Steel consumption
	'Independent' variables	- GDP/Capita	- GDP/capita
	Aggregation level	- Worldwide, 16 regions	- UK
	Remarks	- Classical example of the Intensity of Use approach	- IU approach (scenario 1) and constant consumption (scenario 2)
2-3	Exogenous model inputs	-	-
	Dependent variables	-	-
	'Independent' variables	-	-
	Aggregation level	-	-
	Remarks	-	- Unclear how trade is treated, demand = production?
3-4	Exogenous model inputs	-	- Share of EAF and BOF
	Dependent variables	-	- Production per technology
	'Independent' variables	-	- Set (exogenous input)
	Aggregation level	-	- UK, two technologies (EAF, BOF)
	Remarks	-	- Scrap availability not regarded a problem
4-5	Exogenous model inputs	-	- Specific Energy Consumption function
	Dependent variables	-	- Energy consumption and CO_2 emissions
	'Independent' variables	-	- Set
	Aggregation level	-	- UK, two technologies, total energy use, no CO_2 emissions
	Remarks	-	

Step		**15 VLEEM** **Projections 2000-2100, data 1970-2000** **(Vleem, 2005)**	**16 Malenbaum** **Projections 1985 and 2000, data 1934-1975** **)Malenbaum, 1978)**
0-1	Exogenous model inputs	-	-
	Dependent variables	-	-
	Independent variables	-	-
	Aggregation level	-	-
	Remarks	-	-
1-2	Exogenous model inputs	- GDP, Population	- GDP, Population
	Dependent variables	- Steel consumption	- Steel consumption
	'Independent' variables	- GDP/Capita	- GDP/Capita
	Aggregation level	- Worldwide, 10 regions	- Worldwide, 16 regions
	Remarks	- IU approach	- Classical example of the Intensity of Use approach
2-3	Exogenous model inputs	-	-
	Dependent variables	- Steel production	-
	'Independent' variables	-	-
	Aggregation level	-	-
	Remarks	- Trade kept constant to 2000 levels	-
3-4	Exogenous model inputs	- Share of EAF	-
	Dependent variables	- Production per technology	-
	'Independent' variables	- Set	-
	Aggregation level	- Two technologies (EAF and BOF)	-
	Remarks	-	-
4-5	Exogenous model inputs	- Specific energy consumption function	-
	Dependent variables	- Energy Consumption	-
	'Independent' variables	- No independent variables, specific energy consumption function is exogenous variable	-
	Aggregation level	- Total energy consumption	-
	Remarks	-	-

Step		**17 Groenenberg** **Projections for the coming decades, data 1985-1994** **(Groenenberg, 2000)**	
0-1	Exogenous model inputs	-	
	Dependent variables	-	
	Independent variables	-	
	Aggregation level	-	
	Remarks	-	
1-2	Exogenous model inputs	-	
	Dependent variables	-	
	'Independent' variables	-	
	Aggregation level	-	
	Remarks	-	
2-3	Exogenous model inputs	-GDP per capita	
	Dependent variables	-Crude steel production	
	'Independent' variables	-GDP per capita	
	Aggregation level	-5 regions, classified according to income	
	Remarks	- Based on an analysis of historical data, future growth rates for steel production are projected for countries in five income categories	
3-4	Exogenous model inputs	-	
	Dependent variables	-	
	'Independent' variables	-	
	Aggregation level	-	
	Remarks	-	
4-6	Exogenous model inputs	-	
	Dependent variables	-	
	'Independent' variables	-	
	Aggregation level	-	
	Remarks	-	

Other models with steel demand as function of independent variables

Step		**18 Mark C. Roberts, No projections, data for 1960-1995 (Roberts, 1996)**	**19 Mark C. Roberts No projections, data 1960-1995 (Roberts, 1996)**
0-1	Exogenous model inputs	-	- GDP
	Dependent variables	-	- Consumption of products
	Independent variables	-	- Production composition of income - GDP
	Aggregation level	-	-World, 4 ‘products’ (Personal consumption, government expenditures, private investment, net exports)
	Remarks	-	-
1-2	Exogenous model inputs	- GDP	-
	Dependent variables	- Metal consumption	- Metal consumption
	‘Independent’ variables	- GDP, Time	- Consumption of products - Material composition of product - Time
	Aggregation level	- World	- World, 4 ‘products’ World, 4 ‘products’ (Personal consumption, government expenditures, private investment, net exports)
	Remarks	- Simple IU formulation with 3 constants, including time as variable	-
2-3	Exogenous model inputs	-	-
	Dependent variables	-	-
	‘Independent’ variables	-	-
	Aggregation level	-	-
	Remarks	-	-
3-4	Exogenous model inputs	-	-
	Dependent variables	-	-
	‘Independent’ variables	-	-
	Aggregation level	-	-
	Remarks	-	-
4-6	Exogenous model inputs	-	-
	Dependent variables	-	-
	‘Independent’ variables	-	-
	Aggregation level	-	-
	Remarks	-	-

Step		**20 Raymundo M. Valdes** **No projections, data 1957-1987** **(Valdes, 1990)**	**21 Prem R. Lohani and John E. Tilton** **No projections, data 1977-1987** **(Lohani and Tilon, 1993)**
0-1	Exogenous model inputs	- GDP, Population, Share of construction and manufacturing in total GDP, Share of traditional versus high-tech sectors	-
	Dependent variables	- Consumption of products	-
	Independent variables	- Share of construction and manufacturing in GDP - Share of traditional versus high-tech sectors - GDP	-
	Aggregation level	- Australia	-
	Remarks	- The independent variables mentioned are used as drivers for the product composition of income	-
1-2	Exogenous model inputs	-	- GDP, Population
	Dependent variables	- Metal consumption	- Metal consumption
	‘Independent’ variables	- Steel prices - Time	- GDP - Time
	Aggregation level	- Australia	- 30 Less developed countries
	Remarks	- The independent variables mentioned are used as drivers for the material composition of products.	- Both time and GDP per capita should be used as independent variables
2-3	Exogenous model inputs	-	-
	Dependent variables	-	-
	‘Independent’ variables	-	-
	Aggregation level	-	-
	Remarks	-	-
3-4	Exogenous model inputs	-	-
	Dependent variables	-	-
	‘Independent’ variables	-	-
	Aggregation level	-	-
	Remarks	-	-
4-6	Exogenous model inputs	-	-
	Dependent variables	-	-
	‘Independent’ variables	-	-
	Aggregation level	-	-
	Remarks	-	-

Appendix 3 Overview data sources

Variable	Region	Years	Source	Notes
Crude steel production	All	1970-2003	IISI, various years	1,2
	2,14,15, 16,23	1900-1969	Wirtschaftvereinigung Stahl (2004)	2
	1,3,4,5,6,7,8,9,10,11,12,13, 17,18,19,20,21,22,24,25,26	1955-1969	IISI, 1972	3
	11	1900-1954	Wirtschaftvereinigung Stahl (2004)	4
	1,3,4,5,6,7,8,9,10,12,13,17, 18,19,20,21,22,24,25,26	1900-1954	IISI, various years	5
Pig iron production	All	1970-2003	IISI, various years	1,2
	2,14,15, 16,23	1900-1969	Wirtschaftvereinigung Stahl (2004)	2
	11	1900-1954	Wirtschaftvereinigung Stahl (2004)	6
	1,3,4,5,6,7,8,9,10,12,13,17, 18,19,20,21,22,24,25,26	1900-1969	Wirtschaftvereinigung Stahl (2004)	7
Technology shares	All	1979-2003	IISI, various years	8
Direct reduced iron production	All	1970-2003	Midrex, 2003	9
Foundry ratio	2	1938-2003	USGS, Various years WSD, 2005	10
Apparent crude steel consumption	All	1970-2003	IISI, various years	11
Circulating scrap ratio	All	1972-2003	IISI, various years	12
Scrap trade	All	1979-2003	IISI, various years	13
	2	1937-1978	Kelly and Fenton (2004a)	
PI trade	All	2000-2003	IISI, WSIF, various years	14
	All	1979-1999	IISI, various years	15
	2	1909-1978 1990-1999	Kelly and Fenton (2004b)	
DRI trade	2	1987-2002	Kelly and Fenton (2004b)	16
Population	All	1970-2100	TIMER	17
Population	All	1900-1969	Van Vuuren et al. (1999)	18
GDP / capita	All	1970-2100	TIMER	17

[1] Based on the Statistical yearbook of 1980 (data 1970-1979), 1990 (1980-1989), 2000 (1990-1999) and 2004 (2000-2003).
[2] USSR data split into region 14,15 and 16 using division of production in 1992.
[3] Central America split into region 3-6 using division of production in 1970,1971 and 1972. Other Africa split into region 7,8,9 and 26 using division of production in 1970, 1971 and 1972. Other Asia split into region 19,21,22 and 25 using division of production in 1970,1971 and 1972. Western Europe split into region 11 and 13 using division of production in 1970, 1971 and 1972.
[4] EU figures translated into Western Europe figures based on a factor derived from production data for 1955, 1956 and 1957 for Western Europe (see note 3) and for the EU from Wirtshaftsvereinigung Stahl (2004).
[5] Total worldwide steel production minus known regions is split using division of production in 1955, 1956 and 1957.

[6] EU figures from source translated into Western Europe figures based on a factor derived from production data for 1970,1971 and 1972 for Western Europe (see note 1) and for the EU from Wirtshaftsvereinigung Stahl (2004).

[7] Total worldwide pig iron production minus known regions is split using division of production in 1970, 1971 and 1972.

[8] Before 1979, 100% BOF assumed (4.4.2). Based on the Statistical yearbook of 1980 (data 1979), 1990 (1989), 2000 (1990-1999) and 2004 (2000-2003). Between 1979 and 1989, linear interpolation used.

[9] Before 1970, no direct reduced iron production assumed. For 1970-1979, division between regions for 1980 used.

[10] Foundry ratio for the US applied to all regions (Section 3.3.2 and Section 3.4.2).

[11] Before 1970, apparent crude steel consumption set equal to crude steel production.

[12] For assumptions before 1972, see Section 4.4.4. For unknown years, linear interpolation used.

[13] Based on the Statistical yearbook of 1980 (data 1979), 1990 (1980-1989), 2000 (1990-1999) and 2004 (2000-2003). Before 1979, scrap trade not included except for the US.

[14] Based on world steel in figures 2002 (data 2000), 2003 (data 2001), 2004 (data 2002), 2005 (data 2003).

[15] Based on statistical yearbook 1980 (data 1979) and 1990 (data 1980-1989). Between 1990 and 2000, linear interpolation used, expect for US, where independent data source was available. Before 1979, pig iron trade not include, expect for the US.

[16] For other regions, direct reduced iron trade not included.

[17] Towards the future, 4 scenarios are distinguished. Data in 1995$ are within the model converted to purchasing power parity (ppp) figures based on a personal communication with Detlef van Vuuren (2005).

[18] The 13 regions distinguished are divided into 26 regions using the division of 1970.

Appendix 4 Parameters used in IU_{cap} curve

For all regions except region 1 (Canada), 2 (USA), 11 (Western Europe), 14 (Ukraine+), 19 (Korea), 20 (China), 23 (Japan) and 24 (Oceania), we use the basic IU_{cap} curve given in Figure 3-8 (Section 3.4.1). To avoid large deviations from historical data in the year following 2003, we calculate the absolute difference between the historical data and the basic IU_{cap} curve in 2003. In the years following 2003, this absolute difference is gradually decreased as a function of per capita income to a value of 0 at a per capita income of 20000 1995 ppp $. The formulas used in this correction are:

$$\Delta IU_{cap}(2003) = IU_{cap,historical,2003} - \alpha * e^{(\beta / GDP_{cap,ppp,2003})}$$

Equation A4-1

$$IU_{cap,t} = \alpha * e^{(\beta / GDP_{cap,ppp,t})} + \frac{(20000 - GDP_{cap,ppp,t})}{(20000 - GDP_{cap,ppp,2003})} * \Delta IU_{cap}(2003)$$

Equation A4-2

In Table A4-1, the parameters used in the IU_{cap} curve are given.

Table A4-1 Parameters used in IU_{cap} curve

Region	α	β	GDP_{cap} (2003)[1]	ΔIU_{cap} (2003)[1]
1. Canada	783	-9254		
2. USA	523	-9254		
3. Mexico	635	-9254	8343	-3
4. Rest Central America	635	-9254	3584	-15
5. Brazil	635	-9254	6902	-67
6. Rest South America	635	-9254	6396	-82
7. Northern Africa	635	-9254	4123	-4
8. Western Africa	635	-9254	1088	7
9. Eastern Africa	635	-9254	1057	4
10. South Africa	635	-9254	9160	-136
11. Western Europe	601	-9254		
12. Central Europe	635	-9254	8850	-12
13. Turkey	635	-9254	5864	79
14. Ukraine +	635	-3794		
15. Central Asia	635	-9254	2549	10
16. Russia +	635	-9254	6950	-1
17. Middle East	635	-9254	5951	34
18. India	635	-9254	2439	19
19. Korea	861	-2814		
20. China+	635	-4817		
21. South Eastern Asia	635	-9254	3760	47
22. Indonesia+	635	-9254	2885	-3
23. Japan	861	-9254		
24. Oceania	583	-9254		
25. Other South Asia	635	-9254	1670	6
26. Other South Africa	635	-9254	1285	15

[1] For those regions where we use Equation A4-2 (Section 3.4.1).

Appendix 5 Summary scenario storylines

The text below is taken from Nakicenovic (2000):

The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

The B1 storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reduction in materials intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, included improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Appendix 6 Projected population and GDP per capita values

A1	CAN	USA	MEX	RCEA	BRA	RSAM	NAF	WEA	EAF	SAF	WEU	CEU	TUR	UKR	CAS	RUS	MIE	IND	KOR	CHI	SEA	IND	JAP	OCE	RSAS	RSAF	WRL
2000	31	285	99	74	172	176	142	307	197	44	390	129	68	64	56	162	170	1017	69	1307	309	217	127	26	346	106	6089
2010	32	308	112	85	190	200	166	386	246	44	393	129	78	62	63	161	210	1146	72	1375	351	241	129	28	424	123	6754
2020	34	335	122	94	204	221	186	455	290	40	400	127	83	60	70	159	251	1246	73	1413	386	260	131	31	500	135	7306
2030	36	362	129	103	214	241	201	514	331	35	409	124	87	58	76	155	287	1304	74	1415	416	273	132	34	568	144	7721
2040	38	385	133	110	221	256	212	566	367	31	415	121	88	55	81	151	320	1328	73	1381	435	282	133	36	626	152	7997
2050	39	404	136	115	225	268	220	609	399	29	424	118	87	52	85	146	350	1323	71	1331	448	285	132	39	667	159	8158
2060	40	418	136	120	225	277	226	645	419	27	429	115	84	50	87	141	371	1289	69	1281	448	279	133	38	695	170	8210
2070	40	419	133	123	221	281	227	665	429	26	428	109	79	47	87	138	382	1228	65	1187	435	265	131	37	705	177	8064
2080	40	415	128	122	212	278	228	668	428	24	421	102	74	45	86	134	389	1145	61	1095	417	250	130	36	694	178	7798
2090	40	418	121	121	201	271	225	661	422	23	412	102	68	44	82	132	389	1054	57	997	398	234	129	35	672	177	7484
2100	37	387	114	117	190	259	216	638	405	21	386	97	61	42	76	128	369	924	51	874	358	208	120	33	611	170	6890

A2	CAN	USA	MEX	RCEA	BRA	RSAM	NAF	WEA	EAF	SAF	WEU	CEU	TUR	UKR	CAS	RUS	MIE	IND	KOR	CHI	SEA	IND	JAP	OCE	RSAS	RSAF	WRL
2000	31	285	99	74	172	176	142	307	197	44	390	129	68	64	56	162	170	1017	69	1307	309	217	127	26	346	106	6089
2010	32	308	116	87	196	206	174	406	257	45	391	129	81	63	66	162	218	1198	71	1386	360	248	129	28	440	126	6923
2020	34	336	134	102	220	239	211	530	336	46	395	128	94	61	77	159	278	1395	72	1462	411	278	128	31	551	150	7859
2030	37	364	149	116	243	271	246	676	429	47	401	125	105	59	88	156	338	1569	73	1507	458	304	127	34	666	179	8767
2040	38	387	161	129	262	300	278	836	531	48	405	122	114	57	98	153	396	1717	73	1534	499	328	126	36	777	210	9616
2050	39	405	171	140	278	324	305	989	630	50	406	118	120	55	106	149	448	1827	72	1543	533	348	125	39	870	240	10329
2060	39	422	180	150	291	345	329	1141	729	53	404	115	126	54	113	146	496	1915	71	1546	558	362	124	40	946	271	10966
2070	39	438	187	159	302	363	349	1278	817	56	404	113	131	53	117	144	536	1971	72	1572	578	373	123	41	1001	297	11512
2080	40	454	195	167	313	380	366	1396	893	58	411	112	134	53	121	144	569	1998	73	1614	594	383	123	42	1036	319	11985
2090	40	466	202	175	324	395	380	1483	950	60	420	112	138	54	123	147	594	1993	76	1681	606	389	125	42	1047	335	12357
2100	40	476	207	180	335	406	390	1532	980	61	431	114	140	55	124	150	612	1942	80	1762	609	390	127	43	1027	343	12556

B1	CAN	USA	MEX	RCEA	BRA	RSAM	NAF	WEA	EAF	SAF	WEU	CEU	TUR	UKR	CAS	RUS	MIE	IND	KOR	CHI	SEA	IND	JAP	OCE	RSAS	RSAF	WRL
2000	31	285	99	74	172	176	142	307	197	44	390	129	68	64	56	162	170	1017	69	1307	309	217	127	26	346	106	6089
2010	32	308	112	85	190	200	166	386	246	44	393	129	78	62	63	161	210	1146	72	1375	351	241	129	28	424	123	6754
2020	34	335	122	94	204	221	186	455	290	40	400	127	83	60	70	159	251	1246	73	1413	386	260	131	31	500	135	7306
2030	36	362	129	103	214	241	201	514	331	35	409	124	87	58	76	155	287	1304	74	1415	416	273	132	34	568	144	7721
2040	38	385	133	110	221	256	212	566	367	31	415	121	88	55	81	151	320	1328	73	1381	435	282	133	36	626	152	7997
2050	39	404	136	115	225	268	220	609	399	29	424	118	87	52	85	146	350	1323	71	1331	448	285	132	39	667	159	8158
2060	40	418	136	120	225	277	226	645	419	27	429	115	84	50	87	141	371	1289	69	1281	448	279	133	38	695	170	8210
2070	40	419	133	123	221	281	227	665	429	26	428	109	79	47	87	138	382	1228	65	1187	435	265	131	37	705	177	8064
2080	40	415	128	122	212	278	228	668	428	24	421	102	74	45	86	134	389	1145	61	1095	417	250	130	36	694	178	7798
2090	40	418	121	121	201	271	225	661	422	23	412	102	68	44	82	132	389	1054	57	997	398	234	129	35	672	177	7484
2100	37	387	114	117	190	259	216	638	405	21	386	97	61	42	76	128	369	924	51	874	358	208	120	33	611	170	6890

B2	CAN	USA	MEX	RCEA	BRA	RSAM	NAF	WEA	EAF	SAF	WEU	CEU	TUR	UKR	CAS	RUS	MIE	IND	KOR	CHI	SEA	IND	JAP	OCE	RSAS	RSAF	WRL
2000	31	285	99	74	172	176	142	307	197	44	390	129	68	64	56	162	170	1017	69	1307	309	217	127	26	346	106	6089
2010	33	314	113	86	193	202	170	395	251	45	396	127	78	60	62	155	211	1174	72	1402	356	245	128	28	432	125	6854
2020	35	343	125	96	209	227	197	494	313	44	397	124	86	56	68	147	258	1312	74	1470	399	269	126	30	522	146	7569
2030	37	368	134	106	221	249	218	601	380	42	395	120	93	52	73	138	302	1416	75	1495	434	287	121	32	609	168	8165
2040	38	388	139	113	229	265	237	710	449	41	390	114	97	48	76	129	346	1485	74	1486	458	299	116	33	686	189	8635
2050	39	404	140	117	232	275	249	813	516	41	381	107	99	43	77	119	384	1531	72	1443	474	305	110	34	750	209	8966
2060	38	410	141	121	231	282	257	900	574	40	367	101	99	40	77	111	415	1554	69	1388	482	306	104	34	800	226	9168
2070	38	418	139	122	227	284	261	971	620	40	355	95	99	37	76	104	437	1553	66	1335	482	304	98	34	834	239	9269
2080	37	422	136	122	222	282	260	1026	656	40	347	91	97	35	74	99	451	1534	63	1288	478	299	94	34	850	248	9284
2090	37	426	132	121	215	277	257	1061	681	40	342	88	95	34	72	96	459	1499	62	1254	471	292	91	33	852	253	9238
2100	36	428	128	118	210	271	252	1078	693	39	340	87	93	33	70	96	461	1457	61	1231	462	285	90	33	842	254	9147

Table A6-1 Population projections (millions) for the 26 TIMER regions

A1	CAN	USA	MEX	RCEA	BRA	RSAM	NAF	WEA	EAF	SAF	WEU	CEU	TUR	UKR	CAS	RUS	MIE	IND	KOR	CHI	SEA	IND	JAP	OCE	RSAS	RSAF	WRL
2000	25699	31798	8287	5036	6783	6514	4150	1041	1095	8750	22662	8184	5718	3758	2192	6175	5883	2218	9684	4041	3686	2700	24001	21232	1590	1232	6851
2010	31644	39532	10173	6068	8394	7991	5057	1249	1282	10892	27880	11872	6961	5948	3610	9152	6929	3160	13614	6633	5296	4142	28478	26810	2251	1582	8720
2020	40782	51210	14261	8391	11692	11145	6164	1568	1611	14086	36254	16766	8930	8534	5251	12477	8515	4707	19175	11046	8143	6801	35573	34646	3367	2138	11864
2030	50619	63597	19880	11719	16210	15585	7917	2073	2128	18319	45403	23687	11699	12604	8022	17410	10753	7058	26137	17720	12066	10567	42935	43308	5093	3076	16070
2040	60996	75363	27546	16521	22230	21690	10715	2931	3023	23994	54413	33239	15803	18887	12586	24566	14152	10658	34264	26999	17385	15828	50148	52543	7805	4732	21442
2050	74696	89676	37912	23484	30258	30066	15054	4238	4371	31620	65759	46207	21869	27790	19310	34268	19425	15846	43799	39447	24740	23213	58756	65213	11748	7360	28680
2060	89169	103920	50281	32305	39572	40037	21102	6108	6289	41091	77306	61440	29684	39145	28047	45932	26505	22875	54024	54018	33795	32398	67209	78869	17156	11087	37254
2070	102811	116817	63576	42349	49324	50603	28939	8690	8931	52029	87872	77386	38689	52063	38009	58683	35132	31888	64136	69320	43837	42620	74813	91811	24129	16004	46479
2080	115379	128535	77284	53014	59210	61317	38429	12145	12482	64146	97460	93509	48487	66083	48820	71944	44802	43030	74180	85119	54482	53510	81706	103688	32732	22038	56422
2090	126767	139077	90792	63546	68820	71646	49229	16623	17125	77101	106034	109146	58716	80253	60082	84854	54963	55973	83843	100707	65129	64497	87910	114415	42615	28992	66842
2100	136982	148512	103616	73381	77825	81301	60736	22180	22968	90400	113632	123812	69065	93678	71454	96898	65054	70054	93680	115584	75357	75035	93472	124633	53137	36450	76924

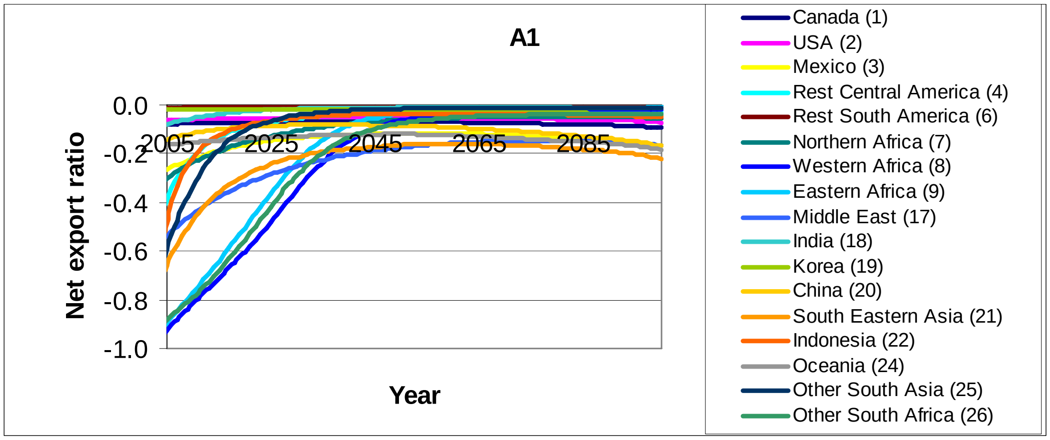
A2	CAN	USA	MEX	RCEA	BRA	RSAM	NAF	WEA	EAF	SAF	WEU	CEU	TUR	UKR	CAS	RUS	MIE	IND	KOR	CHI	SEA	IND	JAP	OCE	RSAS	RSAF	WRL
2000	25699	31798	8287	5036	6783	6514	4150	1041	1095	8750	22662	8184	5718	3758	2192	6175	5883	2218	9684	4041	3686	2700	24001	21232	1590	1232	6851
2010	30248	37758	9596	5716	7920	7539	4846	1196	1227	10367	26630	11101	6609	5429	3547	8424	6662	2887	12413	5970	4809	3688	27327	25710	2071	1510	8065
2020	35625	44665	11673	6822	9574	9082	5405	1357	1399	12165	31600	13605	7721	6635	4352	9975	7526	3599	14839	7985	6133	4938	31450	30504	2581	1827	9339
2030	40644	51165	14193	8208	11582	10996	6245	1592	1641	14272	36339	16560	9082	8269	5621	11986	8602	4450	17296	10336	7595	6346	35323	35208	3193	2267	10694
2040	45358	56680	17033	9816	13771	13115	7369	1941	2009	16816	40421	20126	10761	10304	7329	14378	9921	5475	19473	12693	9168	7931	38981	39687	3941	2899	12039
2050	50061	61963	20044	11581	16072	15369	8770	2410	2505	19744	44364	23715	12813	12487	9132	16881	11562	6719	21644	15322	10871	9683	42398	44310	4854	3707	13516
2060	54690	67007	23160	13458	18458	17719	10393	2990	3118	22895	48149	27311	15196	14816	11017	19469	13438	8159	23888	18173	12693	11563	45604	48956	5908	4638	15102
2070	59245	71866	26374	15457	20926	20159	12205	3674	3842	26198	51801	30943	17805	17262	12943	22145	15523	9781	26272	21226	14628	13567	48654	53557	7097	5679	16860
2080	63873	76755	29771	17632	23547	22772	14198	4463	4677	29625	55476	34806	20619	19903	15023	24988	17803	11604	28810	24552	16736	15750	51710	58156	8432	6826	18866
2090	68551	81652	33326	19979	26306	25552	16370	5362	5627	33147	59154	38885	23654	22718	17278	27970	20267	13632	31498	28158	19017	18102	54759	62691	9916	8080	21130
2100	73258	86538	37028	22488	29186	28491	18714	6373	6696	36759	62818	43170	26864	25693	19725	31074	22919	15864	34281	32038	21464	20625	57790	67197	11553	9435	23718

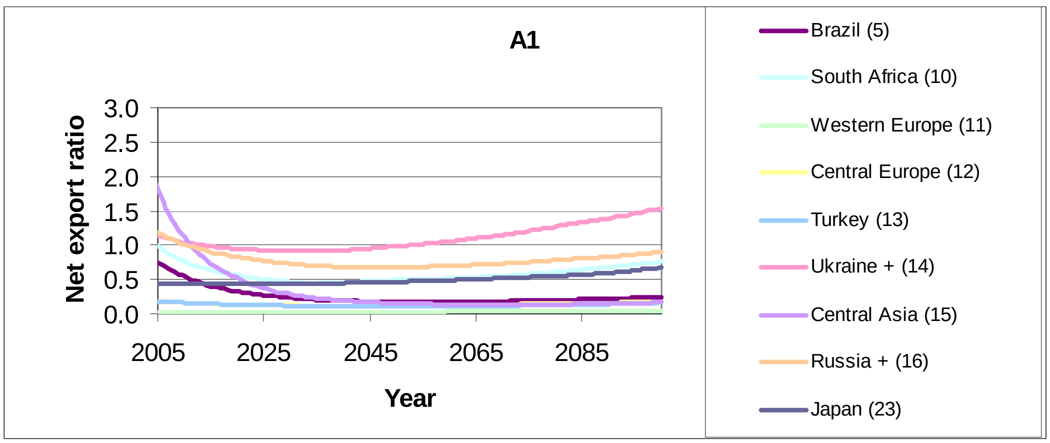
B1	CAN	USA	MEX	RCEA	BRA	RSAM	NAF	WEA	EAF	SAF	WEU	CEU	TUR	UKR	CAS	RUS	MIE	IND	KOR	CHI	SEA	IND	JAP	OCE	RSAS	RSAF	WRL
2000	25699	31798	8287	5036	6783	6514	4150	1041	1095	8750	22662	8184	5718	3758	2192	6175	5883	2218	9684	4041	3686	2700	24001	21232	1590	1232	6851
2010	31108	38845	9924	5921	8190	7795	4970	1227	1259	10705	27395	11533	6843	5758	3504	8855	6809	3047	13029	6351	5075	3966	28056	26348	2167	1549	8497
2020	38820	48678	13120	7716	10761	10231	5857	1481	1525	13419	34465	15334	8504	7774	4739	11416	8095	4235	17069	9682	7224	6016	34066	32961	3007	2003	10958
2030	47090	58881	17414	10226	14105	13482	7245	1885	1962	17011	42286	20550	10899	10723	6662	14958	9994	6002	21762	14311	10136	8867	40249	40040	4280	2800	14141
2040	55784	68345	23267	13848	18502	17899	9489	2584	2739	21797	49978	27796	14482	15238	9834	20063	12941	8734	27082	20554	14116	12875	46216	47442	6316	4244	18161
2050	66464	79384	31318	19234	24630	24279	13041	3651	3870	28048	58836	37746	19625	21945	14833	27321	17399	12658	33516	29337	19578	18456	52956	57127	9275	6482	23625
2060	76539	89274	40573	25854	31483	31634	17817	5124	5420	35501	66893	49050	26005	30228	21135	35711	23188	17780	40146	39292	26089	25154	58947	66399	13195	9528	29810
2070	85700	97958	50288	33270	38508	39284	23881	7113	7510	43905	74011	60640	33188	39441	28156	44681	30116	24198	46560	49525	33164	32425	64188	74837	18138	13447	36350
2080	93899	105659	60108	41020	45505	46914	31080	9720	10260	53026	80289	72156	40855	49258	35623	53834	37744	31968	52866	59907	40533	40015	68837	82355	24114	18148	43302
2090	101147	112444	69630	48550	52210	54158	39127	13034	13786	62615	85765	83166	48739	59023	43265	62593	45631	40827	58899	70001	47790	47540	72942	88997	30851	23457	50527
2100	107511	118407	78556	55468	58422	60837	47561	17072	18142	72328	90510	93359	56634	68136	50879	70641	53351	50311	65168	79501	54668	54603	76562	95555	37893	29045	57407

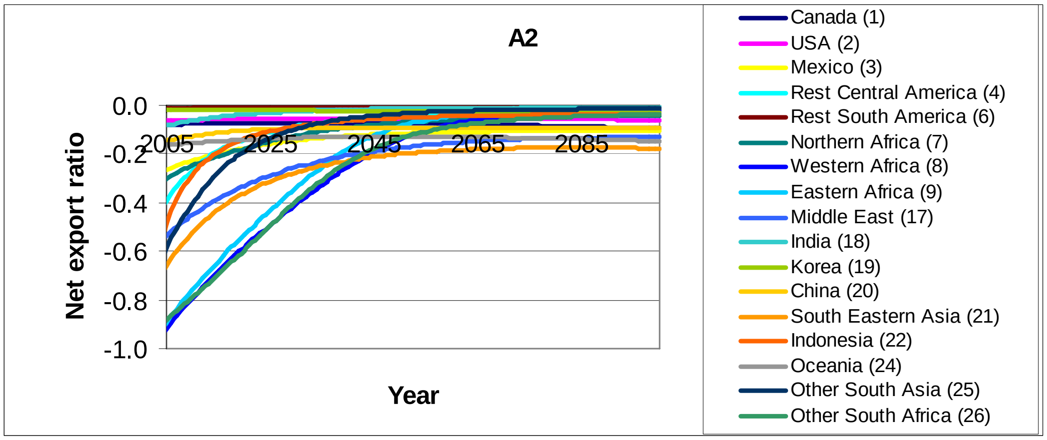
B2	CAN	USA	MEX	RCEA	BRA	RSAM	NAF	WEA	EAF	SAF	WEU	CEU	TUR	UKR	CAS	RUS	MIE	IND	KOR	CHI	SEA	IND	JAP	OCE	RSAS	RSAF	WRL
2000	25699	31798	8287	5036	6783	6514	4150	1041	1095	8750	22662	8184	5718	3758	2192	6175	5883	2218	9684	4041	3686	2700	24001	21232	1590	1232	6851
2010	30725	38629	9953	5932	8268	7880	5060	1233	1262	10707	27149	11883	6785	6238	4198	9475	6804	3060	13949	6807	4857	3742	28173	26278	2192	1558	8568
2020	36492	45773	12793	7497	10127	9614	5889	1433	1487	12965	33194	15429	8063	9353	7106	13305	7781	4170	19577	11391	6204	5031	34121	31869	3006	1943	10816
2030	41272	51766	16030	9333	12304	11683	6862	1677	1737	15554	38751	20121	9332	13133	10933	17710	8675	5497	25219	16864	7710	6509	39445	36723	3978	2456	13127
2040	46494	57985	20121	11750	15147	14454	8403	2161	2259	19115	43466	26048	11316	17665	15652	22789	10191	7314	31215	23540	9724	8538	44180	41875	5334	3324	15805
2050	52469	64727	24894	14695	18564	17850	10770	3027	3223	23950	48490	32500	14325	22249	20099	27818	12652	9715	36742	30212	12260	11137	49023	47851	7137	4702	18757
2060	58865	71975	30235	18085	22452	21751	13969	4354	4682	29860	53892	39725	18096	27158	24667	33137	15747	12806	42315	37132	15255	14230	54149	54304	9468	6591	22068
2070	65646	79764	36167	21987	26801	26142	17784	6129	6618	36440	59679	47862	22381	32685	29744	38995	19316	16534	48510	45067	18718	17811	59641	61002	12279	8856	25988
2080	72937	88120	42679	26385	31609	31026	22222	8398	9098	43655	65867	56910	27180	38812	35406	45351	23370	20942	55330	54071	22667	21897	65514	67922	15590	11512	30553
2090	80764	97066	49747	31270	36870	36405	27299	11227	12192	51457	72469	66859	32505	45462	41768	52124	27907	26059	62783	64214	27114	26503	71786	75192	19422	14571	35860
2100	89165	106644	57373	36658	42581	42307	33043	14692	15983	59833	79513	77738	38321	52620	48913	59299	32956	31926	70848	75603	32087	31664	78484	82851	23816	18043	41982

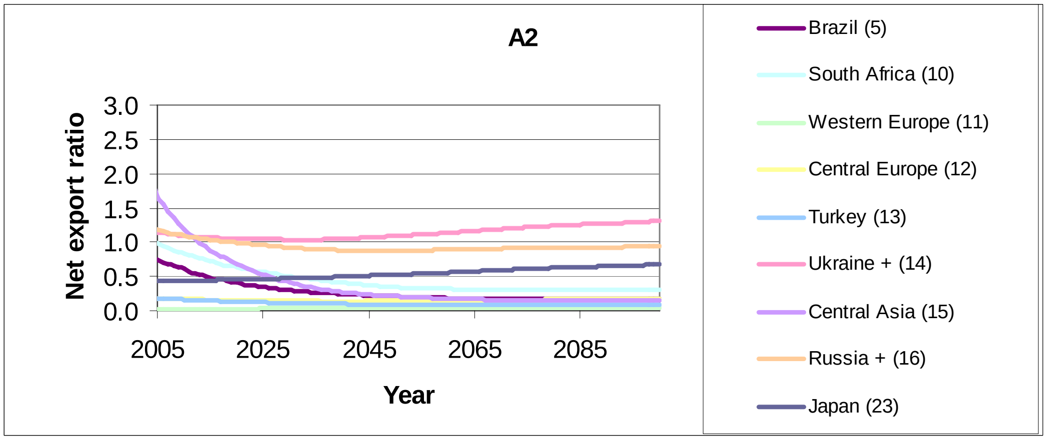
Table A6-2 GDP per capita (1995 ppp $) projections for the 26 TIMER regions

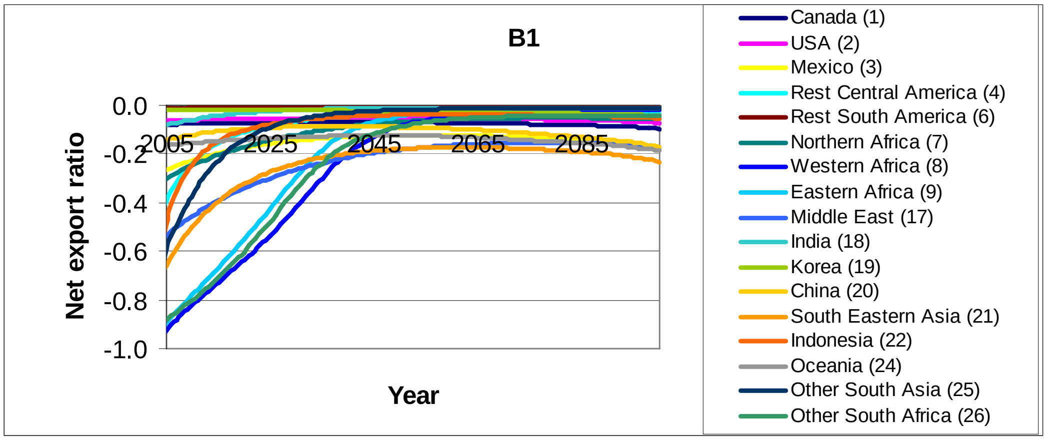
Appendix 7 Default trade projections

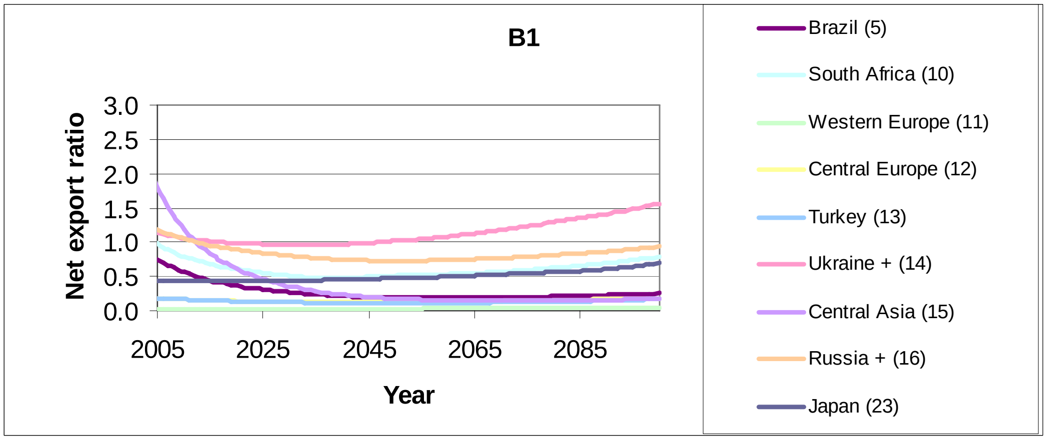





A2
Net export ratio
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
2005
2025
2045
2065
2085
Year
Canada (1)
USA (2)
Mexico (3)
Rest Central America (4)
Rest South America (6)
Northern Africa (7)
Western Africa (8)
Eastern Africa (9)
Middle East (17)
India (18)
Korea (19)
China (20)
South Eastern Asia (21)
Indonesia (22)
Oceania (24)
Other South Asia (25)
Other South Africa (26)


A2
Net export ratio
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2005
2025
2045
2065
2085
Year
Brazil (5)
South Africa (10)
Western Europe (11)
Central Europe (12)
Turkey (13)
Ukraine + (14)
Central Asia (15)
Russia + (16)
Japan (23)


B1
Net export ratio
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
2005
2025
2045
2065
2085
Year
Canada (1)
USA (2)
Mexico (3)
Rest Central America (4)
Rest South America (6)
Northern Africa (7)
Western Africa (8)
Eastern Africa (9)
Middle East (17)
India (18)
Korea (19)
China (20)
South Eastern Asia (21)
Indonesia (22)
Oceania (24)
Other South Asia (25)
Other South Africa (26)


B1
Net export ratio
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2005
2025
2045
2065
2085
Year
Brazil (5)
South Africa (10)
Western Europe (11)
Central Europe (12)
Turkey (13)
Ukraine + (14)
Central Asia (15)
Russia + (16)
Japan (23)

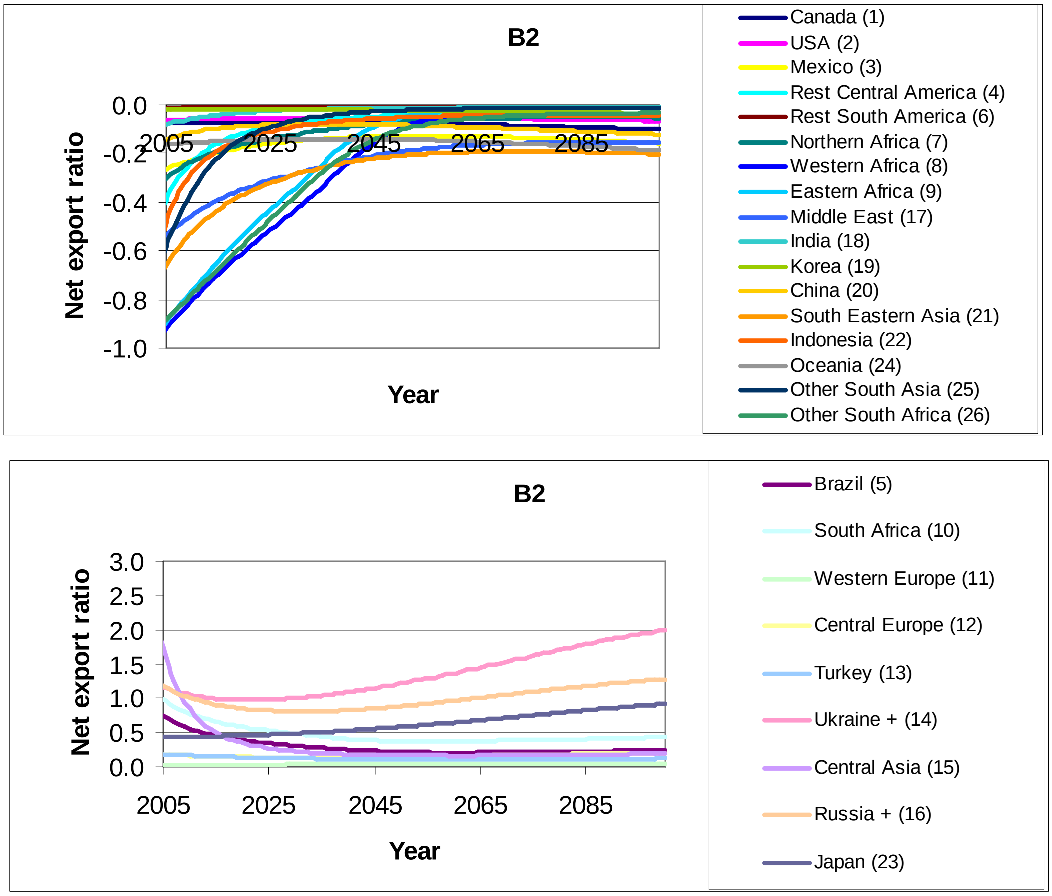


Figure A7-1 **Projected relative trade for net importing and net exporting regions using the frozen trade assumption**

Appendix 8 Alternative trade scenarios

Table A8-1 Regional production in the default trade scenario (absolute trade frozen to 2003 levels) in 2050 and 2100.

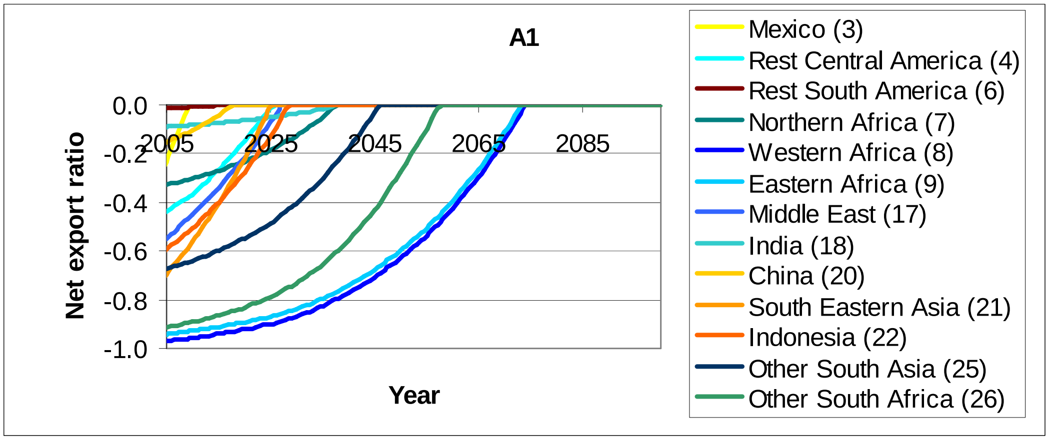
	2050				**2100**			
Production	A1 Change	A2 Change	B1 Change	B2 Change	A1 Change	A2 Change	B1 Change	B2 Change
Canada (1)	18	17	18	18	13	13	13	12
USA (2)	133	127	131	128	94	112	92	102
Mexico (3)	44	45	41	39	29	49	28	31
Rest Central America (4)	35	22	32	25	34	39	32	30
Brazil (5)	91	80	86	78	71	96	69	71
Rest South America (6)	92	72	85	72	78	99	75	73
Northern Africa (7)	51	43	46	44	59	76	57	61
Western Africa (8)	33	14	24	21	139	126	123	193
Eastern Africa (9)	23	9	18	15	90	85	81	131
South Africa (10)	15	19	15	18	11	21	11	16
Western Europe (11)	168	151	165	145	119	124	116	102
Central Europe (12)	50	43	48	43	36	37	35	31
Turkey (13)	30	35	28	30	21	36	21	28
Ukraine+ (14)	42	40	41	38	34	37	34	31
Central Asia (15)	28	22	25	26	26	30	25	23
Russia+ (16)	87	75	84	75	75	73	73	63
Middle East (17)	84	85	80	75	90	120	87	100
India (18)	347	238	305	289	270	371	256	365
Korea (19)	41	39	40	41	22	33	21	26
China (20)	503	479	480	528	235	464	230	342
South Eastern Asia (21)	120	94	107	89	83	110	78	93
Indonesia (22)	86	58	77	58	59	81	56	69
Japan (23)	105	97	104	91	83	83	82	70
Oceania (24)	13	12	12	10	8	10	7	7
Other South Asia (25)	141	62	115	97	171	156	159	190
Other South Africa (26)	21	11	18	15	43	45	40	50

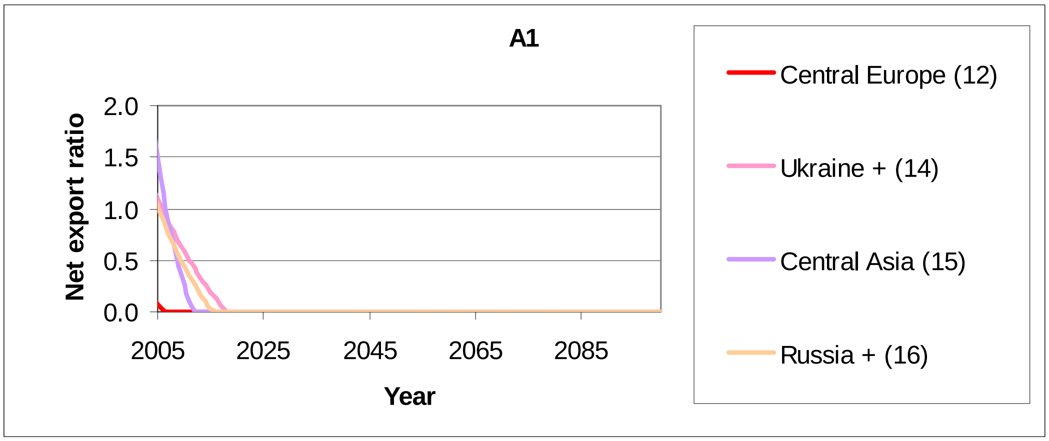
Table A8-2 **Regional production in trade scenario 2 (no trade). Change is compared to default scenario. Changes larger than +/-25% highlighted.**

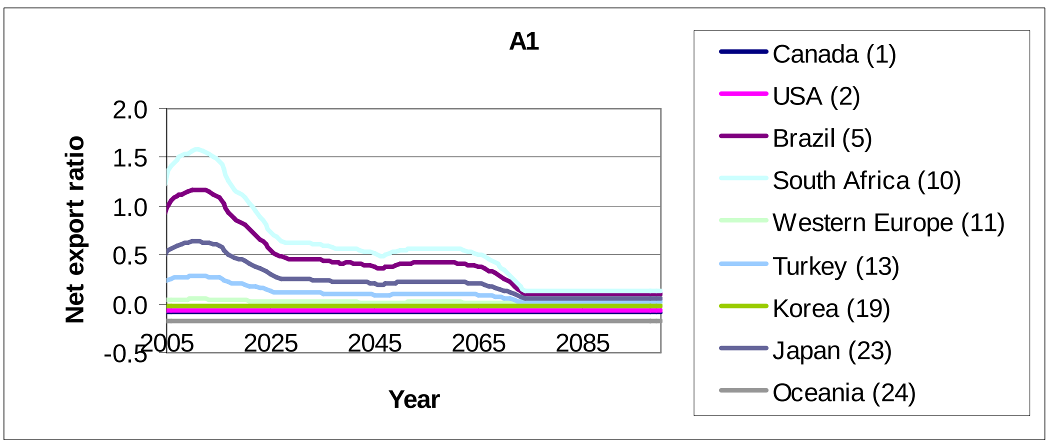
	2050								2100							
Production	A1	Change	A2	Change	B1	Change	B2	Change	A1	Change	A2	Change	B1	Change	B2	Change
Canada (1)	20	107%	19	108%	19	108%	19	108%	14	111%	15	110%	14	111%	14	111%
USA (2)	140	105%	134	106%	138	105%	135	106%	101	108%	119	106%	100	108%	109	107%
Mexico (3)	50	113%	50	113%	47	114%	45	115%	35	120%	54	112%	34	121%	37	119%
Rest Central America (4)	36	103%	23	105%	33	104%	26	105%	35	103%	40	103%	33	104%	31	104%
Brazil (5)	77	85%	67	83%	72	84%	64	82%	57	80%	82	86%	55	80%	57	80%
Rest South America (6)	92	100%	72	100%	86	100%	72	100%	78	100%	99	100%	75	100%	73	100%
Northern Africa (7)	55	107%	47	108%	49	107%	48	108%	63	106%	80	104%	60	106%	64	106%
Western Africa (8)	36	107%	16	116%	26	110%	23	111%	142	102%	129	102%	126	102%	196	101%
Eastern Africa (9)	24	104%	10	110%	18	105%	16	106%	91	101%	86	101%	82	101%	132	101%
South Africa (10)	10	67%	14	75%	10	66%	13	72%	6	57%	16	77%	6	56%	11	70%
Western Europe (11)	163	97%	146	97%	160	97%	139	96%	114	96%	119	96%	111	96%	97	95%
Central Europe (12)	45	89%	37	87%	43	89%	38	87%	30	85%	31	85%	30	85%	26	83%
Turkey (13)	27	90%	32	91%	26	90%	27	90%	18	86%	33	92%	18	85%	25	89%
Ukraine+ (14)	21	50%	19	48%	20	50%	17	45%	14	39%	16	43%	13	39%	10	33%
Central Asia (15)	24	87%	18	83%	21	85%	23	86%	23	86%	26	87%	21	85%	20	84%
Russia+ (16)	52	60%	40	53%	49	58%	40	53%	39	53%	38	52%	38	52%	28	44%
Middle East (17)	102	121%	103	121%	98	122%	93	124%	108	120%	138	115%	105	121%	118	118%
India (18)	351	101%	241	101%	308	101%	293	101%	273	101%	374	101%	259	101%	368	101%
Korea (19)	42	102%	40	102%	41	102%	42	102%	22	104%	34	103%	22	105%	27	104%
China (20)	551	109%	526	110%	528	110%	575	109%	283	120%	511	110%	278	121%	390	114%
South Eastern Asia (21)	144	120%	118	125%	131	122%	113	126%	107	128%	133	122%	102	130%	117	125%
Indonesia (22)	89	104%	61	105%	81	104%	61	105%	62	105%	84	104%	59	106%	72	105%
Japan (23)	72	68%	63	65%	70	68%	57	63%	50	60%	49	60%	48	59%	36	52%
Oceania (24)	14	114%	13	115%	14	114%	12	116%	9	122%	12	117%	9	123%	9	123%
Other South Asia (25)	143	102%	64	104%	117	102%	99	102%	173	101%	158	101%	162	101%	193	101%
Other South Africa (26)	23	108%	13	116%	20	110%	16	112%	45	104%	47	104%	42	104%	52	103%

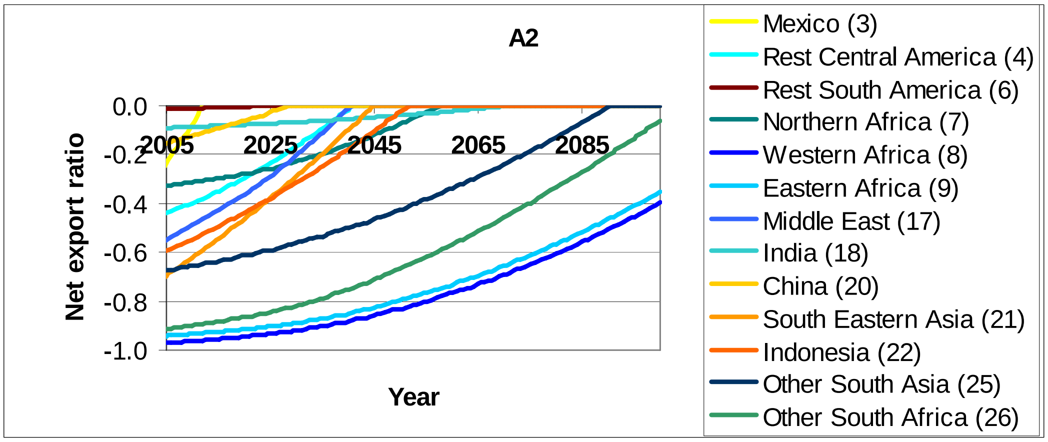
Table A8-3 **Regional production in trade scenario 3 (region specific relative trade). Change is compared to default scenario. Changes larger than +/-25% highlighted.**

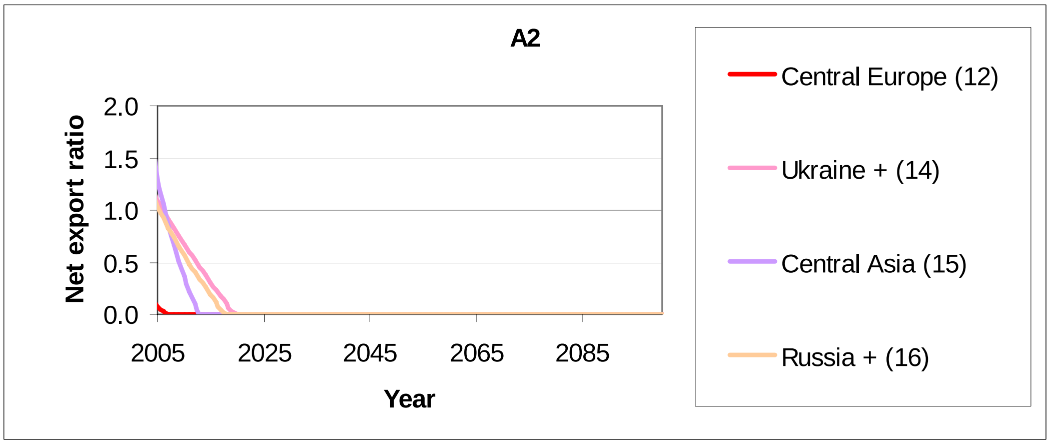
	2050								2100							
Production	A1	Change	A2	Change	B1	Change	B2	Change	A1	Change	A2	Change	B1	Change	B2	Change
Canada (1)	18	99%	17	99%	18	99%	17	99%	13	102%	13	102%	13	102%	13	102%
USA (2)	131	98%	125	98%	129	98%	126	98%	94	100%	111	99%	93	100%	101	100%
Mexico (3)	50	113%	50	113%	47	114%	45	115%	35	120%	54	112%	34	121%	37	119%
Rest Central America (4)	36	103%	23	105%	33	104%	26	105%	35	103%	40	103%	33	104%	31	104%
Brazil (5)	109	119%	109	136%	104	120%	103	132%	63	88%	137	143%	60	88%	63	89%
Rest South America (6)	92	100%	72	100%	86	100%	72	100%	78	100%	99	100%	75	100%	73	100%
Northern Africa (7)	55	107%	43	100%	49	107%	48	108%	63	106%	80	104%	60	106%	64	106%
Western Africa (8)	13	39%	3	20%	8	33%	5	26%	142	102%	78	61%	126	102%	196	101%
Eastern Africa (9)	10	42%	2	22%	6	36%	4	29%	91	101%	56	65%	82	101%	132	101%
South Africa (10)	15	103%	27	139%	15	105%	24	132%	7	64%	30	145%	7	64%	13	80%
Western Europe (11)	166	99%	150	99%	163	99%	143	99%	114	96%	122	98%	112	96%	97	95%
Central Europe (12)	45	89%	37	87%	43	89%	38	87%	30	85%	31	85%	30	85%	26	83%
Turkey (13)	29	99%	37	106%	28	99%	31	104%	19	88%	39	107%	18	88%	25	91%
Ukraine+ (14)	21	50%	19	48%	20	50%	17	45%	14	39%	16	43%	13	39%	10	33%
Central Asia (15)	24	87%	18	83%	21	85%	23	86%	23	86%	26	87%	21	85%	20	84%
Russia+ (16)	52	60%	40	53%	49	58%	40	53%	39	53%	38	52%	38	52%	28	44%
Middle East (17)	102	121%	103	121%	98	122%	93	124%	108	120%	138	115%	105	121%	118	118%
India (18)	351	101%	231	97%	308	101%	292	101%	273	101%	374	101%	259	101%	368	101%
Korea (19)	41	100%	39	100%	40	100%	41	100%	22	102%	33	101%	22	102%	26	102%
China (20)	551	109%	526	110%	528	110%	575	109%	283	120%	511	110%	278	121%	390	114%
South Eastern Asia (21)	144	120%	118	125%	131	122%	113	126%	107	128%	133	122%	102	130%	117	125%
Indonesia (22)	89	104%	60	103%	81	104%	61	105%	62	105%	84	104%	59	106%	72	105%
Japan (23)	87	83%	85	88%	87	84%	77	84%	52	63%	67	81%	51	62%	39	55%
Oceania (24)	12	94%	11	95%	12	95%	10	97%	8	102%	10	98%	8	102%	8	102%
Other South Asia (25)	143	102%	37	59%	110	96%	75	78%	173	101%	158	101%	162	101%	193	101%
Other South Africa (26)	16	78%	4	39%	12	69%	7	49%	45	104%	44	98%	42	104%	52	103%

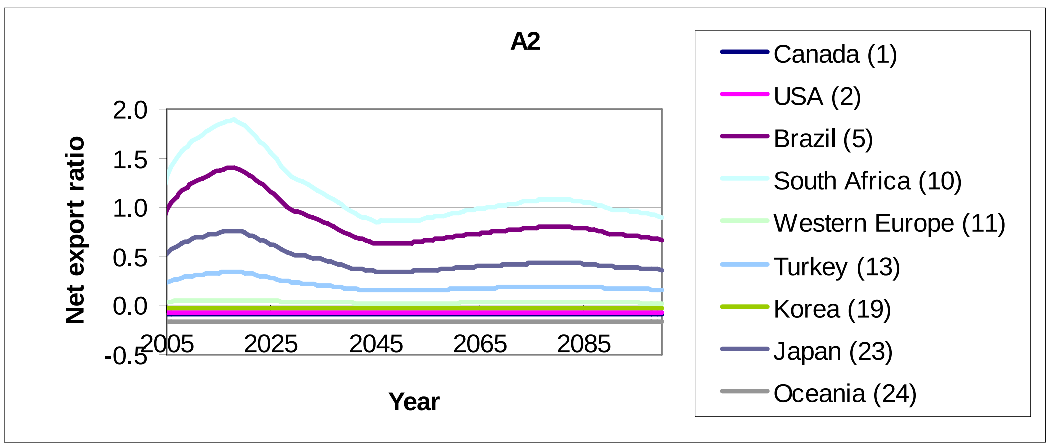

A1
Net export ratio
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
2005
2025
2045
2065
2085
Year
Mexico (3)
Rest Central America (4)
Rest South America (6)
Northern Africa (7)
Western Africa (8)
Eastern Africa (9)
Middle East (17)
India (18)
China (20)
South Eastern Asia (21)
Indonesia (22)
Other South Asia (25)
Other South Africa (26)

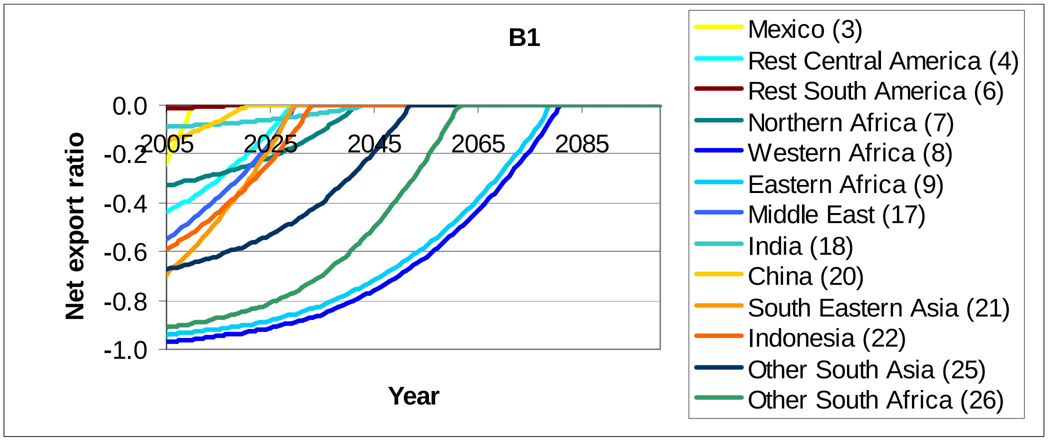

A1
Net export ratio
2.0
1.5
1.0
0.5
0.0
2005
2025
2045
2065
2085
Year
Central Europe (12)
Ukraine + (14)
Central Asia (15)
Russia + (16)

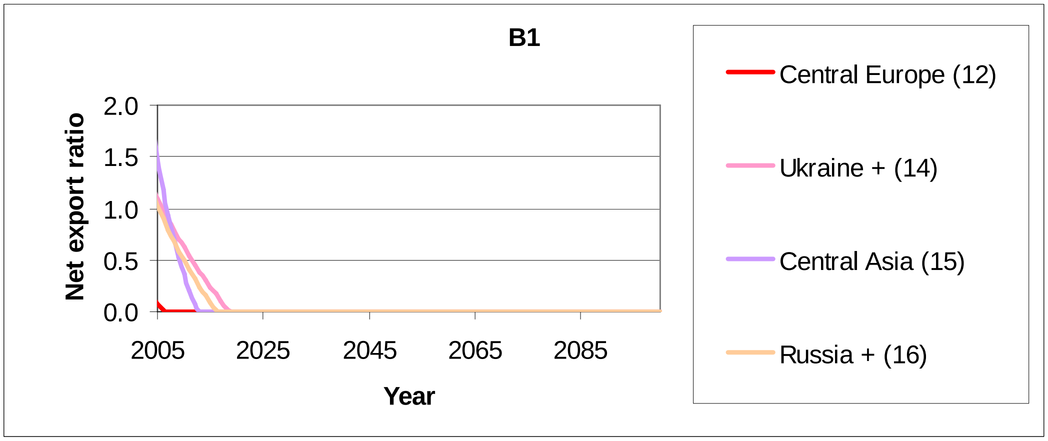

A1
Net export ratio
2.0
1.5
1.0
0.5
0.0
-0.5
2005
2025
2045
2065
2085
Year
Canada (1)
USA (2)
Brazil (5)
South Africa (10)
Western Europe (11)
Turkey (13)
Korea (19)
Japan (23)
Oceania (24)

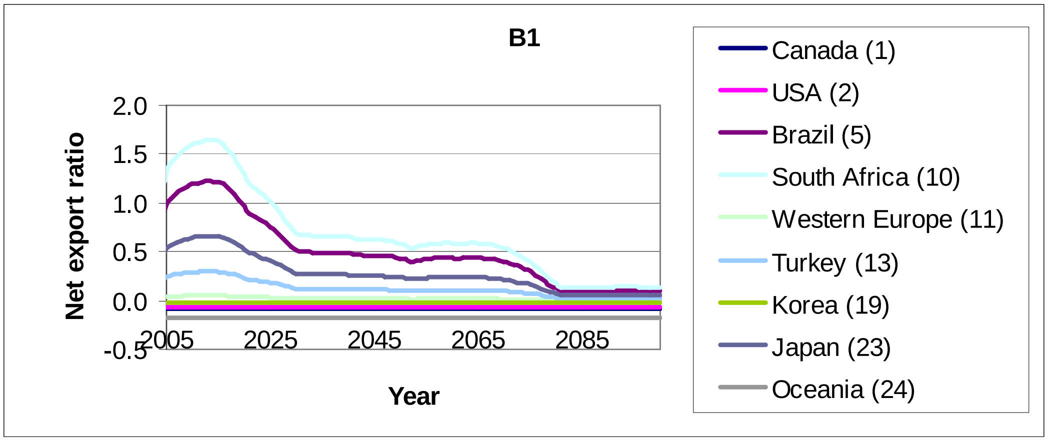

A2
Net export ratio
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
2005
2025
2045
2065
2085
Year
Mexico (3)
Rest Central America (4)
Rest South America (6)
Northern Africa (7)
Western Africa (8)
Eastern Africa (9)
Middle East (17)
India (18)
China (20)
South Eastern Asia (21)
Indonesia (22)
Other South Asia (25)
Other South Africa (26)


A2
Net export ratio
2.0
1.5
1.0
0.5
0.0
2005
2025
2045
2065
2085
Year
Central Europe (12)
Ukraine + (14)
Central Asia (15)
Russia + (16)


A2
Net export ratio
2.0
1.5
1.0
0.5
0.0
-0.5
2005
2025
2045
2065
2085
Year
Canada (1)
USA (2)
Brazil (5)
South Africa (10)
Western Europe (11)
Turkey (13)
Korea (19)
Japan (23)
Oceania (24)


B1
Net export ratio
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
2005
2025
2045
2065
2085
Year
Mexico (3)
Rest Central America (4)
Rest South America (6)
Northern Africa (7)
Western Africa (8)
Eastern Africa (9)
Middle East (17)
India (18)
China (20)
South Eastern Asia (21)
Indonesia (22)
Other South Asia (25)
Other South Africa (26)


B1
Net export ratio
2.0
1.5
1.0
0.5
0.0
2005
2025
2045
2065
2085
Year
Central Europe (12)
Ukraine + (14)
Central Asia (15)
Russia + (16)


B1
Net export ratio
2.0
1.5
1.0
0.5
0.0
-0.5
2005
2025
2045
2065
2085
Year
Canada (1)
USA (2)
Brazil (5)
South Africa (10)
Western Europe (11)
Turkey (13)
Korea (19)
Japan (23)
Oceania (24)

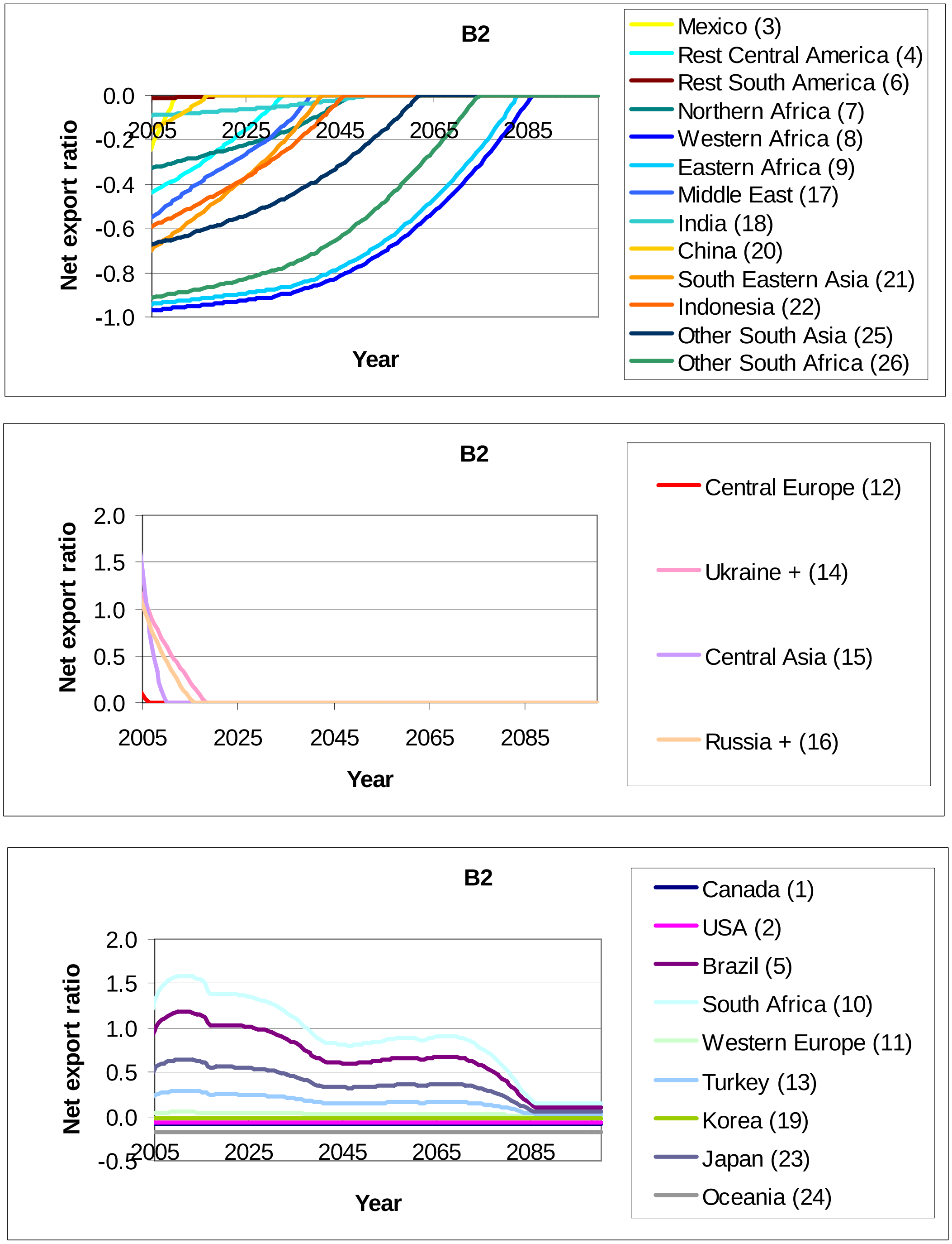


Figure A8-1 Projected relative trade for net importing and net exporting regions using trade assumption 3

Appendix 9 Model script

```
MODULE MAIN;

BEGIN

t.min=1900;
t.max=2100;
t.step=1;
t.sample=1;
t.method=RK2;

CONST

nregion = 27,                       !Timer regions
ntechnologyhist = 3,                !1=OHF, 2=BOF, 3=EAF
ntechnologyfut = 3,                 !1=prim iron bof, 2=prim iron eaf, 3=scrap eaf
nproduct = 4,                       !1= construction, 2=machinery, 3=automotive, 4=others
nhelplifetime=150,                  !Number of dimensions in lifetimedistribution
ntypeofenergy=2,                    !1=fuel, 2=electricity
capacitylifetime=30,                !Lifetime of capacity

ironcontentpi=0.96;                 !Iron content in pig iron

INTEGER

depr,
region,
technologyhist,
technologyfut,
typeofenergy,
product,
helplifetime;

REAL

!EXOGENOUS VARIABLES

pop[nregion](t)=                    FILE("data/pop.dat"),
                                    !Population (millions), scenario dependant from 2000-2100
gdpcap[nregion](t)=                 FILE("data/gdpcap.dat"),
                                    !GDP per capita (1995$), scenario dependant from 2000-2100
```

```
pppfachist[nregion](t)=                          FILE("data/pppfachist.dat"),
                                                 !Historical ppp factor used until 2000
steelconshist[nregion](t)=                       FILE("data/steelconshist.dat"),
                                                 !Historical steel consumption (Mt), 1900-2003
alpha[nregion]=                                  FILE("data/alpha.dat"),
                                                 !Constant in IU curve
beta[nregion]=                                   FILE("data/beta.dat"),
                                                 !Constant in IU curve
matefffactor[nregion](t)=                        FILE("data/matefffactor.dat"),
                                                 !Yearly material efficiency improvement (%) compared to 2003 levels
steelprodtothist[nregion](t)=                    FILE("data/steelprodtothist.dat"),
                                                 !Historical steel production in a region (Mt), 1900-2003
cumsteelprodtot_i[nregion]=                      FILE("data/cumsteelprodtot_i.dat"),
                                                 !Cumulative steel production per region until 1900 (Mt)
sharetechprodhist[ntechnologyhist,nregion](t)=   FILE ("data/sharetechprodhist.dat"),
                                                 !Historical shares of technologies in total steel production (%)
sharedri[nregion](t)=                            FILE ("data/sharedri.dat"),
                                                 !Share DRI in total primary iron production (%)
cumprod_i[ntechnologyhist,nregion](t)=           FILE("data/cumprod_i.dat"),
                                                 !Cumulative production in a region per technology until 1900 (Mt)
foundryratio[nregion](t)=                        FILE("data/foundryratio.dat"),
                                                 !Foundry production as percentage of crude steel production (%)
circscrapratio[nregion](t)=                      FILE("data/circscrapratio.dat"),
                                                 !Fraction of crude steel converted to scrap in the production of finished steel (%)
circscrapratiofoundry[nregion](t)=               FILE("data/circscrapratiofoundry.dat"),
                                                 !Fraction of foundry production converted to scrap (%)
promptscrapratio[nregion](t)=                    FILE("data/promptscrapratio.dat"),
                                                 !Fraction of finished steel converted to scrap in the production of steel products (%)
promptscrapratiofoundry[nregion](t)=             FILE("data/promptscrapratiofoundry.dat"),
                                                 !Fraction of foundry products coverted to scrap before use of the products (%)
touseproductshares[nproduct,nregion](t)=         FILE("data/touseproductshares.dat"),
                                                 !Share of the product groups in total consumption of a region (%)
cumtouseproduct_i[nproduct,nregion]=             FILE("data/cumtouseproduct_i.dat"),
                                                 !Cumulative steel consumption of a region in a certain product group until 1900 (Mt)
stockinuse_i[nproduct,nregion]=                  FILE("data/stockinuse_i.dat"),
                                                 !Stock of a certain product group in use in 1900 (Mt)
lifetimedistribution[nhelplifetime,nproduct]=    FILE("data/lifetimedistribution.dat"),
                                                 !Life time distribution fuction
averagelifetime[nproduct]=                       FILE("data/averagelifetime.dat"),
                                                 !Average life time of steel products (year)
scrapexphist[nregion](t)=                        FILE("data/scrapexphist.dat"),
                                                 !Historical scrap export per region (Mt), 1900-2003
scrapimphist[nregion](t)=                        FILE("data/scrapimphist.dat"),
                                                 !Historical scrap import per region (Mt), 1900-2003
driprodtothist[nregion](t)=                      FILE("data/driprodtothist.dat"),
```

```
                                                                !Historical DRI production in a region (Mt), 1900-2003
piprodtothist[nregion](t)=                                      FILE("data/piprodtothist.dat"),
                                                                !Historical PI productoin in a region (Mt), 1900-2003
cumprimironprodtothist_i[nregion](t)=                           FILE("data/cumprimironprodtothist_i.dat"),
                                                                !Cumulative production of primary iron in a region until 1900 (Mt)
worldcumpiprodtothist_i(t)=                                     FILE("data/worldcumpiprodtothist_i.dat"),
                                                                !Worldwide cumulative production of pig iron until 1900
worldcumdriprodtothist_i(t)=                                    FILE("data/worldcumdriprodtothist_i.dat"),
                                                                !Worldwide cumulative production of direct reduced iron until 1900
specironrequiredhist[ntechnologyhist,nregion](t)=               FILE("data/specironrequiredhist.dat"),
                                                                !Specific iron required per tonne of crude steel before 2003 (tonne / tonne)
specironrequiredfut[ntechnologyfut,nregion](t)=                 FILE("data/specironrequiredfut.dat"),
                                                                !Specific iron requied per tonne of crude steel after 2003 (tonne / tonne)
specironrequiredfoundry[nregion](t)=                            FILE("data/specironrequiredfoundry.dat"),
                                                                !Specific iron input into foundries (tonne / tonne)
driexphist[nregion](t)=                                         FILE("data/driexphist.dat"),
                                                                !Historical DRI export from a region (Mt), 1900-2003
driimphist[nregion](t)=                                         FILE("data/driimphist.dat"),
                                                                !Historical DRI import from a region (Mt), 1900-2003
piexphist[nregion](t)=                                          FILE("data/piexphist.dat"),
                                                                !Historical PI export in a region (Mt), 1900-2003
piimphist[nregion](t)=                                          FILE("data/piimphist.dat"),
                                                                !Historical PI import in a region (Mt), 1900-2003
specscraprequiredhist[ntechnologyhist,nregion](t)=              FILE("data/specscraprequiredhist.dat"),
                                                                !Specific scrap required for the production of crude steel(tonne / tonne input)
specscraprequiredfut[ntechnologyfut,nregion](t)=                FILE("data/specscraprequiredfut.dat"),
                                                                !Specific scrap required for the production of crude steel (tonne / tonne input)

specscraprequiredfoundry[nregion](t)=                           FILE("data/specscraprequiredfoundry.dat"),
                                                                !Specific scrap input into foundries (tonne / tonne input)
futobsscrapproductrecovratioexo[nproduct,nregion](t)=           FILE("data/futobsscrapproductrecovratioexo.dat"),
                                                                !Exogenous obsolete scrap recovery ratio (%)
eeiref[ntypeofenergy,ntechnologyfut,nregion](t)=                FILE("data/eeiref.dat"),
                                                                !Reference energy efficiency indicator in 1990
eeiimpr[ntypeofenergy,ntechnologyfut,nregion](t)=               FILE("data/eeiimpr.dat"),
                                                                !Yearly energy efficiency improvement
sectechnologyref[ntypeofenergy,ntechnologyfut,nregion](t)=      FILE ("data/sectechnologyref.dat"),
                                                                !Reference specific energy consumption (GJ / tonne of crude steel)

!TRADE SCENARIO
tradescenario(t),                                               !Scenario

!CALCULATION OF WORLD POPULATION FROM REGIONAL POPULATION
worldpop(t),                                                    !Total world population (Millions)
```

```
!CALCULATION OF PPP-CORRECTED GDP FIGURES
pppfacchange[nregion](t),               !Variable in formula to calculate ppp correction
pppfacinit[nregion](t),                 !Variable in formula to calculate ppp correction
pppfac[nregion](t),                     !PPP factor for a given region
gdpcapppp[nregion](t),                  !GDP per capita (1995 ppp $)
gdpppp[nregion](t),                     !Total GDP (million 1995 ppp $)
worldgdpppp (t),                        !Total world GDP (million 1995 ppp $)
worldgdpcapppp (t),                     !Overall worldwide GDP per capita (1995 ppp $)
gdp[nregion](t),                        !Total GDP (million 1995$)
worldgdp(t),                            !Total world GDP (million 1995$)
worldgdpcap(t),                         !Total worldwide GDP per capita (1995$)

!TOTAL HISTORICAL AND FUTURE STEEL CONSUMPTION (WITH INTENSITY OF USE CURVE)
iucaphist[nregion](t),                  !Historical intensity of use (tonne / capita)
iucapcalc[nregion](t),                  !Intensity of use, calculated with IU-curve (tonne / capita)
iucap[nregion](t),                      !Intensity of use (tonne/ capita)
timefactor[nregion](t),                 !Moves IU curve as function of time
fitfactor[nregion](t),                  !Moves IU curve to fitted curve as function of GDP/capita
fitparameteralpha[nregion](t),          !Difference between actual and predicted (with IU equation) steel consumption per capita (tonne / capita)
fitparameterbeta[nregion](t),           !Difference between actual per capita income (1995 ppp $) and per capita income of 20000
steelcons[nregion](t),                  !Steel consumption (Mt)
steelconscalib[nregion](t),             !Ratio of calculated steel consumption and historical steel consumption (-)
shareregioncons[nregion](t),            !Share in the worldwide steel consumption for a region (%)
worldsteelcons(t),                      !Total worldwide steel consumption (Mt)
worldsteelconscalib(t),                 !Ratio of calculated worldwide steel consumption and historical worldwide steel consumption
worldiucap(t),                          !Overall worldwide intensity of use (tonne/ capita)

!STEEL TRADE AND PRODUCTION
steelnetexporthist[nregion](t),         !Historical net export of steel (= consumption - production) (Mt)
steelnetexport1[nregion](t),            !Net export of steel (option 1) (Mt)
steelnetexport2[nregion](t),            !Net export of steel (option 2) (Mt)
steelnetexport3[nregion](t),            !Net export of steel (option 3) (Mt)
netexportratio3help1[nregion](t),       !Help variable to balance trade
netexportratio3help2[nregion](t),       !Help variable to balance trade
steelnetexport3help1(t),                !Help variable to balance trade
steelnetexport3help2[nregion](t),       !Help variable to balance trade
steelnetexport3help3(t),                !Help variable to balance trade
steelnetexport3help4(t),                !Help variable to balance trade
steelnetexport[nregion](t),             !Net export of steel = steelnetexporthist before 2003 (Mt)
netexportratio[nregion](t),             !Ratio of net export over steel consumption (%)
worldsteelnetexport(t),                 !Worldwide net export of steel (Mt), should be 0
abssteelnetexport[nregion](t),          !Absolute import or export per region (Mt), for calculation of worldwide trade share
absworldsteelnetexport(t),              !Total worldwide interregional trade (Mt), for calculation of worldwide trade share
absworldnetexportratio(t),              !Ratio of worldwide trade over total steel consumption (%)
steelprodtot[nregion](t),               !Steel production in a region = steelprodtothist before 2003 (Mt)
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worldsteelprodtot(t),                                   !Total worldwide steel production (Mt)
shareregionprod[nregion](t),                            !Share of a region in worldwide production (%)
cumprodtot[nregion](t),                                 !Total cumulative production in a region(Mt)
worldcumprodtot(t),                                     !Total worldwide cumulative production (Mt)

!HISTORICAL STEEL PRODUCTON BY TECHNOLOGY
steelprodhist[ntechnologyhist,nregion](t),              !Steel production, historically, 1900-2003 (Mt)
worldsteelprodhist[ntechnologyhist](t),                 !Worldwide steel production, historically, 1900-2003 (Mt)
cumprodhist[ntechnologyhist,nregion](t),                !Cumulative production, historically, 1900-2003 (Mt)
worldcumprodhist[ntechnologyhist](t),                   !Worldwide cumulative production, historically, 1900-2003 (Mt)

!FOUNDRY PRODUCTION
ironfoundryprod[nregion](t),                            !Production of iron foundries (Mt)
worldironfoundryprod(t),                                !Worldwide production of iron foundries (Mt)

!TOTAL IRON REQUIREMENTS (HISTORICALLY BASED ON TECHNOLOGY-SPECIFIC FACTORS, TO THE FUTURE BASED ON ONE FACTOR)
ironrequiredhist[ntechnologyhist,nregion](t),           !Iron required, historically (Mt)
worldironrequiredhist[ntechnologyhist](t),              !Worldwide iron required, historically (Mt)
irontotrequiredhist[nregion](t),                        !Iron required, historically (Mt)
worldirontotrequiredhist(t),                            !Worldwide iron required, historically (Mt)
ironrequired[ntechnologyfut,nregion](t),                !Iron required
worldironrequired[ntechnologyfut](t),                   !Iron required
irontotrequired[nregion](t),                            !Total iron requirements(Mt)
worldirontotrequired(t),                                !Total worldwide iron requirements (Mt)

!SCRAP AND PRIMARY IRON REQUIREMENTS, HISTORICALLY, BOTTOM-UP (NOT USED FURTHER!)
scraprequiredhist[ntechnologyhist,nregion](t),          !Scrap required, historically (Mt)
scraptotrequiredhist[nregion](t),                       !Total scrap requirements, historically (Mt)
worldscraptotrequiredhist(t),                           !Total worldwide scrap requirements, historically (Mt)
scraptotratiohist[nregion](t),                          !Total scrap requirements as ratio of crude steel production, historically (%)
worldscraptotratiohist(t),                              !Total worldwide scrap requirements as a ratio of crude steel production (%)
primirontotrequiredhist[nregion](t),                    !Total primary iron requirements, historically (Mt)
worldprimirontotrequiredhist(t),                        !Total worldwide primary iron requirements, historically (Mt)
primirontotratiohist[nregion](t),                       !Total primary iron requirements as a ratio of crude steel production, historically (%)
worldprimirontotratiohist(t),                           !Total worldwide primary iron requirements as a ratio of crude steel production (%)
scraprequiredcalib[nregion](t),                         !Ratio of top down scrap requirements and modelled scrap requirements (%)
worldscraprequiredcalib(t),                             !Worldwide ratio of top down scrap requirements and modelled scrap requirements (%)

!PRIMARY IRON AVAILABLE (HISTORICALLY), TOP DOWN AND PRODUCED (FUTURE)
driprodtot[nregion](t),                                 !DRI production (Mt)
piprodtot[nregion](t),                                  !PI production (Mt)
worlddriprodtot(t),                                     !Worldwide DRI production (Mt)
worldpiprodtot(t),                                      !Worldwide PI production (Mt)
primironprodtot[nregion](t),                            !Primary iron production (Mt)
worldprimironprodtot(t),                                !Worldwide primary iron production (Mt)
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cumprimironprodtot[nregion](t),                  !Cumulative primary iron production (Mt)
cumprimironprodtotcap[nregion](t),               !Cumulative production of primary iron per capita (tonne/capita)
worldcumpiprodtot(t),                            !Worldwide cumulative production of pig iron (Mt)
worldcumdriprodtot(t),                           !Worldwide cumulative prdouction of direct reduced iron (Mt)
worldcumprimironprodtot(t),                      !Cumulative worldwide primary iron production
worldcumprimironprodtotcap(t),                   !Worldwide cumulative production of primary iron per capita (tonne/capita)

!SCRAP REQUIREMENTS (HISTORICALLY), TOP DOWN
scraptotrequiredhisttopdown[nregion](t),         !Total scrap requirements, historically top down (Mt)
worldscraptotrequiredhisttopdown(t),             !Total worldwide scrap requirements, historically top down (Mt)
scraptotratiohisttopdown[nregion](t),            !Total scrap requirements (topdown) as a ratio of crude steel production, historically (%)
worldscraptotratiohisttopdown(t),                !Total worldwide scrap requirements (top down) as a ratio of crude steel production (%)
obsoletescraprequiredhisttopdown[nregion](t),    !Total amount of obsolete scrap required (top down), historically (Mt)
worldobsoletescraprequiredhisttopdown(t),        !Total amount of obsolete scrap required (top down), historically, worldwide (Mt)
calcobsscraprecovratiohisttopdown[nregion](t),   !Obsolete scrap (top down) recovery ratio, historically, calculated (%)
calcworldobsscraprecovratiohisttopdown(t),       !Obsolete scrap (top down) recovery ratio, historically, worldwide, calculated (%)
calcscraprecovratiohisttopdown[nregion](t),      !Scrap (top down) recovery ratio, historically, calculated (%)
calcworldscraprecovratiohisttopdown(t),          !Scrap (top down) recovery ratio, historically, worldwide, calculated (%)
scrapavailratiohisttopdown[nregion](t),          !Scrap available (top down) as ratio of scrap requirements, historically (%)
worldscrapavailratiohisttopdown(t),              !Worldwide scrap available (top down) as ratio of scrap requirements, historically (%)

!CIRCULATING SCRAP AVAILABILITY
circscrap[nregion](t),                           !Amount of circulating scrap available (Mt)
worldcircscrap(t),                               !Amount of circulating scrap available, worldwide (Mt)

!PROMPT SCRAP AVAILABILITY
promptscrap[nregion](t),                         !Amount of prompt scrap available (Mt)
worldpromptscrap(t),                             !Amount of prompt scrap available, worldwide (Mt)

!TOTAL MAXIMUM OBSOLUTE SCRAP AVAILABILITY AND CALCULATION OF STOCK IN USE
tousetotal[nregion](t),                          !Amount of steel going to steel stock in use (Mt)
tousetotalratio[nregion](t),                     !Ratio of steel going to steel stock in use and steel consumption (Mt)
touseproduct[nproduct,nregion](t),               !Steel consumption of a region in a certain product group (Mt)
worldtouseproduct[nproduct](t),                  !Worldwide steel consumption in a certain product group (Mt)
worldtousetotal(t),                              !Worldwide amount of steel going to steel stock in use (Mt)
cumtouseproduct[nproduct,nregion](t),            !Cumulative steel consumption in a certain product group (Mt)
cumtousetotal[nregion](t),                       !Cumulative amount of steel going to steel stock in use (Mt)
cumworldtouseproduct[nproduct](t),               !Cumulative worldwide steel consumption in a certain product group (Mt)
cumworldtousetotal(t),                           !Cumulative worldwide amount of steel going to steel stock in use (Mt)
outofuseproduct[nproduct,nregion](t),            !Steel coming out of use in a certian product group (Mt)
worldoutofuseproduct[nproduct](t),               !Worldwide steel coming out of use in a certain product group (Mt)
outofusetotal[nregion](t),                       !Total steel coming out of use (Mt)
worldoutofusetotal(t),                           !Worldwide steel coming out of use (Mt)
stockinuse[nproduct,nregion](t),                 !Stock of a certain product group in use (Mt)
worldstockinuse[nproduct](t),                    !Worldwide stock of a certain product group in use (Mt)
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stockinusetotal[nregion](t),                          !Total steel stock in use, historically (Mt)
stockinusecap[nproduct,nregion](t),                   !Stock in use per capita per product group (tonne/capita)
stockinusetotalcap[nregion](t),                       !Total steel stock in use per capita (tonne/capita)
worldstockinusetotal(t),                              !Worldwide steel stock in use (Mt)
worldstockinusetotalcap(t),                           !Worldwide steel stock in use per capita, historically (tonne/capita)

!TOTAL SCRAP AVAILABILITY, NEGLECTING RECOVERY RATES BUT INCLUDING HISTORICAL SCRAP TRADE
scrapavail[nregion](t),                               !Scrap available for use (Mt)
worldscrapavail(t),                                   !World scrap available for use (Mt)
scrapavailratio[nregion](t),                          !Scrap available as ratio of production (%)
worldscrapavailratio(t),                              !World scrap available as ratio of production (%)

!SCRAP TRADE
scrapimp[nregion](t),                                 !Scrap import (Mt)
scrapexp[nregion](t),                                 !Scrap export (Mt)

!REAL SCRAP AVAILABILITY, BASED ON EXOGENOUS RECOVERY RATES FOR THE FUTURE, TOPDOWN RECOVERY RATES IN THE PAST (HISTORICALLY WITH SCRAP TRADE)
obsscrapproductrecovratioexo[nproduct,nregion](t),    !Obsolete scrap recovery rate as used(%)
obsscrapproduct[nproduct,nregion](t),                 !Real obsolete scrap available per product group, taking into account recovery rate (Mt)
obsscrap[nregion](t),                                 !Real obsolete scrap available, taking into account recovery rate (Mt)
worldobsscrap(t),                                     !Worldwide real obsolete scrap available, taking into account recovery rate (Mt)
realscrapavail[nregion](t),                           !Real total amount of scrap available, taking into account recovery rate (Mt)
worldrealscrapavail(t),                               !Worldwide real total amount of scrap available, taking into account recovery rate (Mt)

!FRACTION OF PRIMARY AND SECONDARY STEEL
secondary[nregion](t),                                !Fraction of secondary iron in total iron input
worldsecondary(t),                                    !Worldwide fraction of secondary iron in total iron input
primary[nregion](t),                                  !Fraction of primary iron in total iron input
worldprimary(t),                                      !Worldwide fraction of primary iron in total iron input

!SHARE OF TECHNOLOGIES AND STEEL PRODUCTION PER TECHNOLOGY
scrapusefoundry[nregion](t),                          !Scrap use in iron foundries (Mt)
sharehelpvariable[ntechnologyfut,nregion](t),         !Help variable for determining share of technologies
sharehelpvariable2[nregion](t),                       !Help variable for determining share of technologies
sharetechprodfut[ntechnologyfut,nregion](t),          !Fraction of technologies (used in projections) in total crude steel production (%)
worldsharetechprodfut[ntechnologyfut](t),             !Worldwide fraction of technologies (used in projections) in total crude steel production (%)
steelprod[ntechnologyfut,nregion](t),                 !Steel production per technology (Mt)
worldsteelprod[ntechnologyfut](t),                    !Worldwide steel production per technology (Mt)

!TOTAL SCRAP USED
scrapused[nregion](t),                                !Actual scrap use (Mt) = realscrapavail until total available scrap exceeds maximum scrap needed
worldscrapused(t),                                    !Worldwide scrap use (Mt)
cumscrapused[nregion](t),                             !Cumulative scrap used (Mt)
worldcumscrapused(t),                                 !Cumulative worldwide scrap used (Mt)
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!STEEL STOCK NO LONGER IN USE
scrapnotusedtopdown[nregion](t),                    !Steel no longer in use (Mt)
worldscrapnotusedtopdown(t),                        !Worldwide steel no longer in use (Mt)
stockoutofusetotaltopdown[nregion](t),              !Stock of steel no longer in use (Mt)
worldstockoutofusetotaltopdown(t),                  !Worldwide stock of steel no longer in use (Mt)

!IRON LOSSES BEFORE STEEL GOING INTO USE
ironlossesbeforeusephase[nregion](t),               !Iron losses before steel going into use (Mt)
worldironlossesbeforeusephase(t),                   !Worldwide iron losses before steel going into use (Mt)
cumironlossesbeforeusephase[nregion](t),            !Cumulative iron losses before steel going into use (Mt)
cumworldironlossesbeforeusephase(t),                !Cumulative worldwide iron losses before steel going into use (Mt)

!CAPACITY OF THREE ROUTES
capacity[ntechnologyfut,nregion](t),                !Capacity required for production via certain technology(Mt)
capacitynew[ntechnologyfut,nregion](t),             !New capacity required per technology (Mt)
capacitydepr[ntechnologyfut,nregion](t),            !Depreciation of capacity (Mt)
calccapacity[ntechnologyfut,nregion](t),            !Real capacity (Mt)

!ENERGY USE
eei[ntypeofenergy,ntechnologyfut,nregion](t),       !Energy efficiency indicator relative to reference
sectechnology[ntypeofenergy,ntechnologyfut,nregion](t),     !Specific energy use (GJ / tonne)
encapacitynew[ntypeofenergy,ntechnologyfut,nregion](t),     !Energy use of newly installed capacity (PJ)
encapacity_ini[ntypeofenergy,ntechnologyfut,nregion](t),    !Energy use of initial capaicty in 1900 (PJ)
encapacitydepr[ntypeofenergy,ntechnologyfut,nregion](t),    !Energy use of depreciated capacity (PJ)
calcencapacity[ntypeofenergy,ntechnologyfut,nregion](t),    !Energy use of real capacity (PJ)
derivedsectechnology[ntypeofenergy,ntechnologyfut,nregion](t),  !Derived specific energy use (GJ / tonne)
encapacity[ntypeofenergy,ntechnologyfut,nregion](t),        !Energy use of capacity (PJ)
entype[ntypeofenergy,nregion](t),                   !Energy use per type of energy carrier (PJ)
entotal[nregion](t),                                !Total energy use (PJ)
worldentype[ntypeofenergy](t),                      !Worldwide energy use per type of energy carrier (PJ)
worldentotal(t),                                    !Total worldwide energy use (PJ)
electricityprodeff[nregion](t),                     !Electricity production efficiency

!CO2 emissions
co2ef[ntypeofenergy,ntechnologyfut,nregion](t),     !CO2 emission factor (t / GJ)
sco2technology[ntypeofenergy,ntechnologyfut,nregion](t),    !Specific CO2 emissions (t / t)
co2capacitynew[ntypeofenergy,ntechnologyfut,nregion](t),    !CO2 emissions of newly installed capacity (Mt)
co2capacity_ini[ntypeofenergy,ntechnologyfut,nregion](t),   !CO2 emissions of initial capacity in 1900 (Mt)
co2capacitydepr[ntypeofenergy,ntechnologyfut,nregion](t),   !CO2 emissions of depreciated capacity (Mt)
calcco2capacity[ntypeofenergy,ntechnologyfut,nregion](t),   !CO2 emissions of real capacity (Mt)
derivedsco2technology[ntypeofenergy,ntechnologyfut,nregion](t), !Derived specific CO2 emissions (t / t)
co2capacity[ntypeofenergy,ntechnologyfut,nregion](t),       !CO2 emissions of capacity (Mt)
co2type[ntypeofenergy,nregion](t),                  !CO2 emissions per type of energy carrier (Mt)
co2total[nregion](t),                               !Total CO2 emissions (Mt)
worldco2type[ntypeofenergy](t),                     !Worldwide CO2 emissions per type of energy carrier (Mt)
```

```
worldco2total(t);                                        !Total worldwide CO2 emissions (Mt)

!SCENARIO
tradescenario=1;

!ELECTRICITY PRODUCTION EFFICIENCY
electricityprodeff[region](t)=0.4,
region=1 to nregion;

!CALCULATION OF WORLD POPULATION FROM REGIONAL POPULATION

!total World population
worldpop=
LSUM(region =1 to nregion, pop[region]);

!CALCULATION OF PPP-CORRECTED GDP FIGURES

!Script below is used by MPN (DVV) to reduce ppp-factor after 2000 towards the ppp factor of the US
pppfacchange[region]=switch(gdpcap[region]=0 ? 1
ELSE 39.680*gdpcap[region]**(-0.38650058)),
region = 1 to nregion;

pppfacinit[region]=switch(t>2000 ? LAST(pppfacinit[region],1)
ELSE pppfacchange[region]),
region=1 to nregion;

pppfac[region]=switch(t>2000 ?
LAST(pppfachist[region],pppfachist[region])*
pppfacchange[region]/pppfacinit[region]*(pppfacinit[2]/pppfacchange[2])
ELSE pppfachist[region]),
region=1 to nregion;

!GDP (ppp) per capita for a region
gdpcapppp[region]=gdpcap[region]*pppfac[region],
region=1 to nregion;

!total GDP (ppp) for a region
gdpppp [region]=
gdpcapppp[region]*pop[region],
region = 1 to nregion;

!total worldwide GDP (ppp)
worldgdpppp=
LSUM(region =1 to nregion, gdpppp[region]);
```

```
!Total worldwide GDP (ppp) / capita
worldgdpcapppp=
worldgdpppp/worldpop;

!Total GDP for a region
gdp[region]=
gdpcap[region]*pop[region],
region=1 to nregion;

!Total worldwide GDP
worldgdp=
LSUM(region =1 to nregion, gdp[region]);

!Total worldwide GDP per capita
worldgdpcap=
worldgdp/worldpop;

!TOTAL HISTORICAL AND FUTURE STEEL CONSUMPTION (WITH INTENSITY OF USE CURVE)

!Steel consumption per capita for a given region, historically
iucaphist[region]=
SWITCH (pop[region]=0 OR t>2003 ? 0
ELSE steelconshist[region]/pop[region]),
region =1 to nregion;

!Intensity of use for a given region, calculated with intensity of use curve
iucapcalc[region]=SWITCH(gdpcapppp[region]=0 ? 1
ELSE (alpha[region]*exp(beta[region]/gdpcapppp[region])/1000)*timefactor[region]+fitfactor[region]),
region=1 to nregion;

!Intensity of use for a given region
iucap[region]=SWITCH(gdpcapppp[region]=0 ? 0, t>2003 ?
(alpha[region]*exp(beta[region]/gdpcapppp[region])/1000)*timefactor[region]+fitfactor[region]
ELSE iucaphist[region]),
region =1 to nregion;

!Factor that moves the IU curve up and down over time
timefactor[region]=SWITCH (t<=2003 ? (1-0.0117)**(t-2003)
ELSE matefffactor[region]**(t-2003)),
region=1 to nregion;

!Factor that brings data in 2003 to standard iucap curve as function of per capita income (gap reduces to 0 when gdpcapppp = 20000)
fitfactor[region]=SWITCH ((region=1) OR (region=2) OR (region=11) OR (region=14) OR (region=19) OR (region=20) OR (region=23) OR (region=24) OR (region=27) OR (fitparameterbeta[region]=0) ? 0,
t>2003 AND gdpcapppp[region]<20000 ? fitparameteralpha[region](2003)-(1-(20000-gdpcapppp[region])/fitparameterbeta[region](2003))*fitparameteralpha[region](2003),
ELSE 0),
```

```
region=1 to nregion;

fitparameteralpha[region]=iucaphist[region]-iucapcalc[region],
region=1 to nregion;

fitparameterbeta[region]= 20000 - gdpcapppp[region],
region=1 to nregion;

!Total steel consumption for a given region
steelcons[region]= iucap[region]*pop[region],
region =1 to nregion;

!Ratio of calculated steel consumption and actual historical steel consumption
steelconscalib[region]=
SWITCH(steelconshist[region]=0 OR t>2003 ? 0
ELSE (iucapcalc[region]*pop[region])/steelconshist[region]),
region=1 to nregion;

!Share in the worldwide steel consumption for a region
shareregioncons[region]=
steelcons[region]/worldsteelcons,
region =1 to nregion;

!Total worldwide steel consumption
worldsteelcons=
LSUM(region =1 to nregion, steelcons[region]);

!Ratio of total worldwide calculated steel consumption and actual historical steel consumption
worldsteelconscalib=
SWITCH (t>2003 OR worldsteelcons=0 ? 0
ELSE (LSUM(region=1 to nregion, iucapcalc[region]*pop[region]))/worldsteelcons);

!Total worldwide steel consumption per capita
worldiucap=
worldsteelcons/worldpop;

!STEEL TRADE AND PRODUCTION

!Net export of steel, historically
steelnetexporthist[region]=SWITCH (t>2003 ? 0 ELSE
steelprodtothist[region]-steelconshist[region]),
region=1 to nregion;

!Net export of steel, tradescenario 2
steelnetexport2[region]=0,
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```
region=1 to nregion;

!Net export of steel, tradescenario 1
steelnetexport1[region]=steelnetexporthist[region](2003),
region=1 to nregion;

!Help variables to balance trade, tradescenario3

netexportratio3help1[region]=SWITCH(((region=3) OR (region=4) OR (region=6) OR (region=7) OR (region=8) OR (region=9) OR (region=17)
OR (region=18) OR (region=20) OR (region=21) OR (region=22) OR (region=25) OR (region=26)) AND (t>2003) AND (gdpcapppp[region]<10000) ?
((10000-gdpcapppp[region])/(10000-gdpcapppp[region](2003)))*netexportratio[region](2003),
((region=12) OR (region=14) OR (region=15) OR (region=16)) AND t>2003 AND t<2036 AND (steelcons[region]>0 AND steelprodtot[region](2003)*(2035-t)/31-steelcons[region]>0) ?
(steelprodtot[region](2003)*(2035-t)/31-steelcons[region])/steelcons[region],
((region=1) OR (region=2) OR (region=5) OR (region=10) OR (region=11) OR (region=13) OR (region=19) OR (region=23) OR (region=24)) AND t>2003 ? netexportratio[region](2003)
ELSE 0),
region=1 to nregion;

steelnetexport3help1=LSUM(region=1 to nregion, netexportratio3help1[region]*steelcons[region]);

steelnetexport3help2[region]=SWITCH((region=5 OR region=11 OR region=10 OR region=13 OR region=23) AND t>2003 ?
netexportratio3help1[region]*steelcons[region]
ELSE 0),
region =1 to nregion;

steelnetexport3help3=SWITCH(t>2003 ? LSUM(region=1 to nregion, steelnetexport3help2[region])
ELSE 0);

steelnetexport3help4=SWITCH(t<2003 OR steelnetexport3help3=0 ? 0
ELSE (-steelnetexport3help1+steelnetexport3help3)/(steelnetexport3help3));

netexportratio3help2[region]=SWITCH((region=5 OR region=11 OR region=10 OR region=13 OR region=23) AND t>2003 ?
netexportratio3help1[region]*steelnetexport3help4
ELSE netexportratio3help1[region]),
region=1 to nregion;

!Net export of steel, tradescenario 3
steelnetexport3[region]=netexportratio3help2[region]*steelcons[region],
region=1 to nregion;

!Net export of steel
steelnetexport[region]=SWITCH((tradescenario=1) AND (t>2003) ? steelnetexport1[region],
(tradescenario=2) AND (t>2003) ? steelnetexport2[region],
(tradescenario=3) AND (t>2003) ? steelnetexport3[region]
ELSE steelnetexporthist[region]),
region =1 to nregion;
```

```
!Ratio of net export over steel consumption
netexportratio[region]=SWITCH (steelcons[region]=0 ? 1
ELSE steelnetexport[region]/steelcons[region]),
region=1 to nregion;

!Worldwide net export (should in principle be 0)
worldsteelnetexport=LSUM(region=1 to nregion, steelnetexport[region]);

!Absolute trade flow for the calculation of the percentage of trade worldwide, historically
abssteelnetexport[region]=SWITCH(steelnetexport[region]>0 ? steelnetexport[region]
ELSE -steelnetexport[region]),
region=1 to nregion;

!Absolute amount of interregional trade, historically
absworldsteelnetexport=(LSUM(region=1 to nregion, abssteelnetexport[region]))/2;

!Ratio of interregional trade over total steel consumption, historically
absworldnetexportratio=SWITCH (worldsteelcons=0 ? 1
ELSE absworldsteelnetexport/worldsteelcons);

!Total production in a region
steelprodtot[region]=SWITCH (t>2003 ? steelcons[region]+steelnetexport[region]
ELSE steelprodtothist[region]),
region=1 to nregion;

!Total world steel production
worldsteelprodtot=
LSUM(region =1 to nregion, steelprodtot[region]);

!Calculation of share of each region in world production
shareregionprod[region]=
SWITCH (worldsteelprodtot =0 ? 0
ELSE steelprodtot[region]/worldsteelprodtot),
region=1 to nregion;

!Total cumulative production in a region
cumprodtot[region]=INTEG(steelprodtot[region],cumsteelprodtot_i[region]),
region=1 to nregion;

!Total worldwide cumulative production
worldcumprodtot=
LSUM(region=1 to nregion, cumprodtot[region]);

!HISTORICAL STEEL PRODUCTION BY TECHNOLOGY
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!Production in a region per technology, historically
steelprodhist[technologyhist,region]=
SWITCH (t>2003 ? 0
ELSE sharetechprodhist[technologyhist,region]*steelprodtothist[region]),
technologyhist=1 to ntechnologyhist,
region =1 to nregion;

!World production per technology, historically
worldsteelprodhist[technologyhist]=
LSUM(region=1 to nregion, steelprodhist[technologyhist,region]),
technologyhist=1 to ntechnologyhist;

!Cumulative production in a region per technology, historically
cumprodhist[technologyhist,region]=
INTEG(steelprodhist[technologyhist,region],cumprod_i[technologyhist,region]),
technologyhist=1 to ntechnologyhist,
region=1 to nregion;

!Cumulative worldwide production per technology, historically
worldcumprodhist[technologyhist]=
LSUM(region=1 to nregion, cumprodhist[technologyhist,region]),
technologyhist =1 to ntechnologyhist;

!FOUNDRY PRODUCTION

!Iron foundry production
ironfoundryprod[region]=foundryratio[region]*steelcons[region],
region=1 to nregion;

!Total world foundry iron production
worldironfoundryprod=LSUM(region=1 to nregion, ironfoundryprod[region]);

!TOTAL IRON REQUIREMENTS

!Total iron required per technology per region, historically
ironrequiredhist[technologyhist,region]=
SWITCH (t>2003 ? 0
ELSE steelprodhist[technologyhist,region]*specironrequiredhist[technologyhist,region]),
technologyhist=1 to ntechnologyhist,
region=1 to nregion;

!Total iron required per technology worldwide, historically
worldironrequiredhist[technologyhist]=SWITCH (t>2003 ? 0
ELSE LSUM(region=1 to nregion, ironrequiredhist[technologyhist,region])),
```

```
technologyhist =1 to ntechnologyhist;

!Total iron required per region, historically
irontotrequiredhist[region]=LSUM(technologyhist=1 to ntechnologyhist, ironrequiredhist[technologyhist,region])+ironfoundryprod[region]*specironrequiredfoundry[region],
region=1 to nregion;

!Total iron required worldwide, historically
worldirontotrequiredhist=LSUM(region=1 to nregion, irontotrequiredhist[region]);

!Total iron required per technology per region, historically
ironrequired[technologyfut,region]=
steelprod[technologyfut,region]*specironrequiredfut[technologyfut,region],
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Total iron required per technology worldwide, historically
worldironrequired[technologyfut]=LSUM(region=1 to nregion, ironrequired[technologyfut,region]),
technologyfut =1 to ntechnologyfut;

!Total iron required
irontotrequired[region]=SWITCH (t>2003 ?
LSUM(technologyfut=1 to ntechnologyfut, ironrequired[technologyfut,region])+specironrequiredfoundry[region]*ironfoundryprod[region],
ELSE irontotrequiredhist[region]),
region =1 to nregion;

!Worldwide iron requirements
worldirontotrequired=
LSUM(region =1 to nregion, irontotrequired[region]);

!SCRAP AND PRIMARY IRON REQUIREMENTS, HISTORICALLY, BOTTOM-UP (NOT USED FURTHER!)

!Scrap required per technology per region, historically
scraprequiredhist[technologyhist,region]=
SWITCH (t>2003 ? 0,
ELSE steelprodhist[technologyhist,region]*specironrequiredhist[technologyhist,region]*specscraprequiredhist[technologyhist,region]),
technologyhist=1 to ntechnologyhist,
region =1 to nregion;

!Scrap required per region, historically
scraptotrequiredhist[region]=
SWITCH (t>2003 ? 0,
ElSE LSUM(technologyhist =1 to ntechnologyhist, scraprequiredhist[technologyhist,region])+ironfoundryprod[region]*specironrequiredfoundry[region]*specscraprequiredfoundry[region]),
region =1 to nregion;

!worldwide scrap requirements, historically
```

```
worldscraptotrequiredhist=
SWITCH (t>2003 ? 0,
ELSE LSUM(region =1 to nregion, scraptotrequiredhist[region]));

!Scrap required as ratio of crude steel and foundry production, historically
scraptotratiohist[region]=
SWITCH (t>2003 OR steelprodtothist[region]=0 ? 0,
ELSE scraptotrequiredhist[region]/(steelprodtothist[region]+ironfoundryprod[region])),
region = 1 to nregion;

!Scrap required as ratio of crude steel production worldwide, historically
worldscraptotratiohist=
SWITCH (t>2003 OR worldsteelprodtot=0 ? 0,
ELSE worldscraptotrequiredhist/(worldsteelprodtot+worldironfoundryprod));

!Primary iron required per region, historically
primirontotrequiredhist[region]=
SWITCH (t>2003 ? 0,
ElSE LSUM(technologyhist =1 to ntechnologyhist, steelprodhist[technologyhist,region]*specironrequiredhist[technologyhist,region]*(1-specscraprequiredhist[technologyhist,region]))
+ironfoundryprod[region]*specironrequiredfoundry[region]*(1-specscraprequiredfoundry[region])),
region =1 to nregion;

!Worldwide primary iron requirements, historically
worldprimirontotrequiredhist=
SWITCH (t>2003 ? 0,
ELSE LSUM(region =1 to nregion, primirontotrequiredhist[region]));

!Primary iron required as ratio of crude steel and foundry production, historically
primirontotratiohist[region]=
SWITCH (t>2003 OR steelprodtot[region]=0 ? 0,
ELSE primirontotrequiredhist[region]/(steelprodtot[region]+ironfoundryprod[region])),
region = 1 to nregion;

!Primary iron required as ratio of crude steel production worldwide, historically
worldprimirontotratiohist=
SWITCH (t>2003 OR worldsteelprodtot=0 ? 0,
ELSE worldprimirontotrequiredhist/(worldsteelprodtot+worldironfoundryprod));

!Ratio of top down scrap requirements and modelled scrap requirements
scraprequiredcalib[region]=
SWITCH (t>2003 OR scraptotrequiredhist[region]=0 ? 0
ELSE scraptotrequiredhisttopdown[region]/scraptotrequiredhist[region]),
region= 1 to nregion;

!Worldwide ratio of top down scrap requirements and modelled scrap requirements
```

```
worldscraprequiredcalib=
SWITCH (t>2003 OR worldscraptotrequiredhist=0 ? 0
ELSE worldscraptotrequiredhisttopdown/worldscraptotrequiredhist);

!PRIMARY IRON PRODUCTION

!DRI production
driprodtot[region]=SWITCH(t>2003 ?
sharetechprodfut[2,region]*steelprodtot[region]*specironrequiredfut[2,region]*(1-specscraprequiredfut[2,region])
ELSE driprodtothist[region]),
region=1 to nregion;

!PI production
piprodtot[region]=SWITCH(t>2003 ?
sharetechprodfut[1,region]*steelprodtot[region]*specironrequiredfut[1,region]*(1-specscraprequiredfut[1,region])
ELSE piprodtothist[region]*ironcontentpi),
region=1 to nregion;

!Total primary iron production per region
primironprodtot[region]=
piprodtot[region]+driprodtot[region],
region=1 to nregion;

!Total worldwide primary iron production
worldprimironprodtot=
LSUM(region=1 to nregion, primironprodtot[region]);

!Worldwide DRI production
worlddriprodtot=
LSUM(region=1 to nregion, driprodtot[region]);

!Worldwide PI production
worldpiprodtot=
LSUM(region=1 to nregion, piprodtot[region]);

!Total cumulative primary iron production per region
cumprimironprodtot[region]=INTEG(primironprodtot[region],
cumprimironprodtothist_i[region]),
region=1 to nregion;

!Total cumulative primary iron production per region per capita
cumprimironprodtotcap[region]=SWITCH(pop[region]=0 ? 0
ELSE cumprimironprodtot[region]/pop[region]),
region=1 to nregion;
```

```
!Total worldwide cumulative pig iron production
worldcumpiprodtot=INTEG(worldpiprodtot,worldcumpiprodtothist_i);

!Total worldwide cumulative direct reduced iron production
worldcumdriprodtot=INTEG(worlddriprodtot,worldcumdriprodtothist_i);

!Total worldwide cumulative primary iron production, historically
worldcumprimironprodtot=
LSUM(region=1 to nregion, cumprimironprodtot[region]);

!Total worldwide cumulative primary iron production per capita, historically
worldcumprimironprodtotcap=worldcumprimironprodtot/worldpop;

!SCRAP REQUIREMENTS (HISTORICALLY), TOP DOWN

!Total scrap requirements top down, historically
scraptotrequiredhisttopdown[region]=
SWITCH(t>2003 ? 0
ELSE irontotrequiredhist[region]-piprodtothist[region]*ironcontentpi+piexphist[region]*ironcontentpi-piimphist[region]*ironcontentpi-driprodtothist[region]+driexphist[region]-driimphist[region]),
region=1 to nregion;

!Total worldwide scrap requirements top down, historically
worldscraptotrequiredhisttopdown=
LSUM(region=1 to nregion, scraptotrequiredhisttopdown[region]);

!Scrap required (top down) as ratio of crude steel production, historically
scraptotratiohisttopdown[region]=
SWITCH (t>2003 OR steelprodtot[region]=0 ? 0,
ELSE scraptotrequiredhisttopdown[region]/(steelprodtot[region]+ironfoundryprod[region])),
region = 1 to nregion;

!Scrap required (top down) as ratio of crude steel production worldwide, historically
worldscraptotratiohisttopdown=
SWITCH (t>2003 OR worldsteelprodtot=0 ? 0,
ELSE worldscraptotrequiredhisttopdown/(worldsteelprodtot+worldironfoundryprod));

!Obsolete scrap required (top down) per region, historically
obsoletescraprequiredhisttopdown[region]=
SWITCH (t>2003 ? 0,
ELSE scraptotrequiredhisttopdown[region]-circscrap[region]-promptscrap[region]),
region=1 to nregion;

!Obsolete scrap required (top down) worldwide, historically
worldobsoletescraprequiredhisttopdown=
LSUM(region = 1 to nregion, obsoletescraprequiredhisttopdown[region]);
```

```
!Obsolete scrap (top down) recovery ratio, historically
calcobsscraprecovratiohisttopdown[region]=
SWITCH (outofusetotal[region]=0 OR t>2003 ? 1
ELSE (obsoletescraprequiredhisttopdown[region]+scrapexphist[region]-scrapimphist[region])/outofusetotal[region]),
region=1 to nregion;

!Worldwide obsolete scrap (top down) recovery ratio, historically
calcworldobsscraprecovratiohisttopdown=
SWITCH (t>2003 OR worldoutofusetotal=0 ? 1
ELSE worldobsoletescraprequiredhisttopdown/worldoutofusetotal);

!Scrap (top down) recovery ratio, historically
calcscraprecovratiohisttopdown[region]=
SWITCH (scrapavail[region]=0 OR t>2003 ? 1
ELSE (scraptotrequiredhisttopdown[region]+scrapexphist[region]-scrapimphist[region])/scrapavail[region]),
region=1 to nregion;

!Worldwide scrap (top down) recovery ratio, historically
calcworldscraprecovratiohisttopdown=
SWITCH (t>2003 OR worldscrapavail=0? 1
ELSE worldscraptotrequiredhisttopdown/worldscrapavail);

!Scrap (top down) availability as ratio of scrap requirements, historically
scrapavailratiohisttopdown[region]=
SWITCH (scraptotrequiredhisttopdown[region]=0 OR t>2003 ? 1
ELSE scrapavail[region]/scraptotrequiredhisttopdown[region]),
region=1 to nregion;

!Worldwide scrap (top down) availability as ratio of worldwide scrap requirements, historically
worldscrapavailratiohisttopdown=
SWITCH (t>2003 OR worldscraptotrequiredhisttopdown=0 ? 1
ELSE worldscrapavail/worldscraptotrequiredhisttopdown);

!CIRCULATING SCRAP AVAILABILITY

!Circulating scrap availability
circscrap[region]=circscrapratio[region]*steelprodtot[region]+circscrapratiofoundry[region]*ironfoundryprod[region],
region=1 to nregion;

!Circulating scrap availability, worldwide
worldcircscrap=LSUM (region =1 to nregion, circscrap[region]);

!PROMPT SCRAP AVAILABILITY
```

```
!Prompt scrap availability
promptscrap[region]=(1-circscrapratio[region])*
promptscrapratio[region]*steelcons[region]+promptscrapratiofoundry[region]*ironfoundryprod[region],
region=1 to nregion;

!Prompt scrap availability, worldwide
worldpromptscrap=LSUM (region =1 to nregion, promptscrap[region]);

!TOTAL MAXIMUM OBSOLETE SCRAP AVAILABILITY AND CALCULATION OF STOCK IN USE

!Steel going to steel stock in use
tousetotal[region]=(steelcons[region]*(1-circscrapratio[region])*(1-promptscrapratio[region])+ironfoundryprod[region]*
(1-promptscrapratiofoundry[region])),
region=1 to nregion;

!Ratio of steel going to steel stock in use and steel consumption
tousetotalratio[region]=
SWITCH(steelcons[region]=0 ? 0
ELSE tousetotal[region]/(steelcons[region]+ironfoundryprod[region])),
region=1 to nregion;

!Steel going to steel stock in use in a certain product group
touseproduct[product,region]=touseproductshares[product,region]*tousetotal[region],
product=1 to nproduct,
region=1 to nregion;

!Worldwide steel going to steel stock in use in a certain product group
worldtouseproduct[product]=LSUM(region=1 to nregion, touseproduct[product,region]),
product=1 to nproduct;

!Worldwide total steel going to steel stock in use
worldtousetotal=
LSUM(product=1 to nproduct, worldtouseproduct[product]);

!Cumulative Steel going to steel stock in use in a certain product group
cumtouseproduct[product,region]=
INTEG (touseproduct[product,region],cumtouseproduct_i[product,region]),
product=1 to nproduct,
region=1 to nregion;

!Cumulative Steel going to steel stock in use
cumtousetotal[region]=LSUM(product=1 to nproduct, cumtouseproduct[product,region]),
region=1 to nregion;

!Cumulative Worldwide steel going to steel stock in use in a certain product group
```

```
cumworldtouseproduct[product]=LSUM(region=1 to nregion, cumtouseproduct[product,region]),
product =1 to nproduct;

!Cumulative Worldwide total steel going to steel stock in use
cumworldtousetotal=
LSUM(product=1 to nproduct, cumworldtouseproduct[product]);

!Steel coming out of use in a certain product group
outofuseproduct[product,region]=
SWITCH ( (t-t.min)<averagelifetime[product] ?
LSUM(helplifetime=1 to nhelplifetime, lifetimedistribution[helplifetime,product]*
NLAST(touseproduct[product,region],helplifetime,0))
+MAX(0,stockinuse_i[product,region]/averagelifetime[product]),
ELSE
LSUM(helplifetime=1 to nhelplifetime, lifetimedistribution[helplifetime,product]*
NLAST(touseproduct[product,region],helplifetime,0))),
product =1 to nproduct,
region= 1 to nregion;

!Worldwide steel coming out of use in a certain product group
worldoutofuseproduct[product]=
LSUM(region=1 to nregion, outofuseproduct[product,region]),
product=1 to nproduct;

!Total steel coming out of use
outofusetotal[region](t)=
LSUM(product=1 to nproduct, outofuseproduct[product,region]),
region=1 to nregion;

!Total worldwide steel coming out of use
worldoutofusetotal(t)=
LSUM(region=1 to nregion, outofusetotal[region]);

!Stock of a certain product in use
stockinuse[product,region]=
INTEG(touseproduct[product,region]-outofuseproduct[product,region],stockinuse_i[product,region]),
product=1 to nproduct,
region=1 to nregion;

!World stock in use of a certain product
worldstockinuse[product]=
LSUM(region=1 to nregion, stockinuse[product,region]),
product=1 to nproduct;

!Stock of steel in use, total
```

```
stockinusetotal[region]=
LSUM(product=1 to nproduct, stockinuse[product,region]),
region=1 to nregion;

!Stcok of steel in use per capita per product group
stockinusecap[product,region]=SWITCH (pop[region]=0 ? 0
ELSE stockinuse[product,region]/pop[region]),
product =1 to nproduct,
region =1 to nregion;

!Stock of steel in use per capita, total
stockinusetotalcap[region]=SWITCH(pop[region]=0 ? 0
ELSE stockinusetotal[region]/pop[region]),
region=1 to nregion;

!Stock of steel in use, worldwide
worldstockinusetotal=
LSUM(region=1 to nregion, stockinusetotal[region]);

!Stock of steel in use, worldwide per capita
worldstockinusetotalcap(t)=
worldstockinusetotal/worldpop;

!TOTAL SCRAP AVAILABILITY, NEGLECTING RECOVERY RATES BUT INCLUDING HISTORICAL SCRAP TRADE

!Total amount of scrap available
scrapavail[region]=
circscrap[region]+promptscrap[region]+outofusetotal[region]+scrapimphist[region]-scrapexphist[region],
region=1 to nregion;

!Total amount of scrap available worldwide
worldscrapavail=
LSUM(region=1 to nregion, scrapavail[region]);

!Scrap availability as ratio of crude steel production
scrapavailratio[region]=SWITCH(steelprodtot[region]=0 ? 1
ELSE scrapavail[region]/(steelprodtot[region]+ironfoundryprod[region])),
region=1 to nregion;

!Worldwide scrap availability as ratio of crude steel production
worldscrapavailratio=
worldscrapavail/(worldsteelprodtot+worldironfoundryprod);

!SCRAP TRADE
scrapimp[region]=SWITCH(t>2003 ? 0,
```

```
ELSE scrapimphist[region]),
region=1 to nregion;

scrapexp[region]=SWITCH(t>2003 ? 0,
ELSE scrapexphist[region]),
region=1 to nregion;

!REAL SCRAP AVAILABILITY, BASED ON EXOGENOUS RECOVERY RATES FOR THE FUTURE, TOPDOWN RECOVERY RATE IN THE PAST (HISTORICALLY WITH SCRAP TRADE)

!Obsolete scrap recovery rate
obsscrapproductrecovratioexo[product,region]=SWITCH(t>2003 AND t < 2020 ?
LAST(obsscrapproductrecovratioexo[product,region],calcobsscraprecovratiohisttopdown[region])
+(futobsscrapproductrecovratioexo[product,region]-calcobsscraprecovratiohisttopdown[region](2003))/17,
t >=2020 ? futobsscrapproductrecovratioexo[product,region],
ELSE calcobsscraprecovratiohisttopdown[region]),
product=1 to nproduct,
region=1 to nregion;

!Real obsolete scrap available per product group
obsscrapproduct[product,region]=obsscrapproductrecovratioexo[product,region]*outofuseproduct[product,region],
product=1 to nproduct,
region=1 to nregion;

!Real obsolete scrap available
obsscrap[region]=LSUM(product =1 to nproduct, obsscrapproduct[product,region]),
region=1 to nregion;

!Real worldwide obsolete scrap available
worldobsscrap=LSUM(region=1 to nregion, obsscrap[region]);

!Real total scrap available
realscrapavail[region]=
circscrap[region]+promptscrap[region]+obsscrap[region]-scrapexp[region]+scrapimp[region],
region=1 to nregion;

!Real total scrap available worldwide
worldrealscrapavail=
LSUM (region=1 to nregion, realscrapavail[region]);

!FRACTION OF SECONDARY AND PRIMARY STEEL,

!Fraction of secondary steel
secondary[region]=SWITCH (irontotrequired[region]=0 ? 0, t>2003 ?
scrapused[region]/irontotrequired[region]
ELSE scraptotrequiredhisttopdown[region]/irontotrequired[region]),
```

```
region =1 to nregion;

!Worldwide fraction of secondary steel
worldsecondary=SWITCH (worldirontotrequired=0 ? 0, t>2003 ?
worldscrapused/worldirontotrequired
ELSE worldscraptotrequiredhisttopdown/worldirontotrequired);

!Fraction of primary steel
primary[region]=1-secondary[region],
region=1 to nregion;

!Worldwide fraction of primary steel
worldprimary=1-worldsecondary;

!FRACTION OF THREE TECHNOLOGIES IN STEEL PRODUCTION AND STEEL PRODUCTION PER TECHNOLOGY

scrapusefoundry[region]=ironfoundryprod[region]*speciron requiredfoundry[region]*specscraprequiredfoundry[region],
region=1 to nregion;

sharehelpvariable[technologyfut,region]=steelprodtot[region]*speciron requiredfut[technologyfut,region]*specscraprequiredfut[technologyfut,region],
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

sharehelpvariable2[region]=SWITCH(sharedri[region]=1 ? 0
ELSE (sharedri[region]*speciron requiredfut[1,region]*(1-specscraprequiredfut[1,region]))/((1-sharedri[region])*speciron requiredfut[2,region]*(1-specscraprequiredfut[2,region]))),
region=1 to nregion;

sharetechprodfut[1,region]=SWITCH(steelprodtot[region]=0 OR (realscrapavail[region]-scrapusefoundry[region]-sharehelpvariable[3,region])>0 OR sharedri[region]=1 ? 0,
sharedri[region]=0 ? (realscrapavail[region]-scrapusefoundry[region]-sharehelpvariable[3,region])/(sharehelpvariable[1,region]-sharehelpvariable[3,region])
ELSE (realscrapavail[region]-scrapusefoundry[region]-sharehelpvariable[3,region])/
(sharehelpvariable[1,region]+sharehelpvariable2[region]*sharehelpvariable[2,region]-sharehelpvariable[3,region]-sharehelpvariable2[region]*sharehelpvariable[3,region])),
region=1 to nregion;

sharetechprodfut[2,region]=SWITCH(steelprodtot[region]=0 OR (realscrapavail[region]-scrapusefoundry[region]-sharehelpvariable[3,region])>0 ? 0,
sharedri[region]=0 ? 0,
sharedri[region]=1 ? (realscrapavail[region]-scrapusefoundry[region]-sharehelpvariable[3,region])/(sharehelpvariable[2,region]-sharehelpvariable[3,region])
ELSE sharetechprodfut[1,region]*sharehelpvariable2[region]),
region=1 to nregion;

!Fraction of Scrap + EAF
sharetechprodfut[3,region]=1-sharetechprodfut[1,region]-sharetechprodfut[2,region],
region=1 to nregion;

!Steel production per technology
steelprod[technologyfut,region]=sharetechprodfut[technologyfut,region]*steelprodtot[region],
```

```
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!World production per technology
worldsteelprod[technologyfut]=
LSUM(region=1 to nregion, steelprod[technologyfut,region]),
technologyfut=1 to ntechnologyfut;

!Wordlwide share of steel production per technology
worldsharetechprodfut[technologyfut]=
worldsteelprod[technologyfut]/worldsteelprodtot,
technologyfut=1 to ntechnologyfut;

!TOTAL SCRAP USED

!total scrapused
scrapused[region]=SWITCH(t>2003 ? LSUM(technologyfut=1 to ntechnologyfut,(sharetechprodfut[technologyfut,region]*sharehelpvariable[technologyfut,region]))
+scrapusefoundry[region]
ELSE scraptotrequiredhisttopdown[region]),
region=1 to nregion;

!World total scrap used
worldscrapused=LSUM(region=1 to nregion, scrapused[region]);

cumscrapused[region]=INTEG(scrapused[region],0),
region=1 to nregion;

worldcumscrapused=INTEG(worldscrapused,0);

!STEEL STOCK NO LONGER IN USE, TOPDOWN

!Scrap not being used
scrapnotusedtopdown[region]=SWITCH(t>2003 ?
outofusetotal[region]-obsscrap[region]
ELSE outofusetotal[region]-obsoletescraprequiredhisttopdown[region]-scrapexphist[region]+scrapimphist[region]),
region=1 to nregion;

!Scrap not being used, worldwide
worldscrapnotusedtopdown=
LSUM (region=1 to nregion, scrapnotusedtopdown[region]);

!Steel stock no longer in use
stockoutofusetotaltopdown[region]=
INTEG(scrapnotusedtopdown[region],0),
region=1 to nregion;
```

```
!Worldside steel stock no longer in use,
worldstockoutofusetotaltopdown=
INTEG (worldscrapnotusedtopdown,0);

!IRON LOSSES BEFORE STEEL GOING INTO USE

!iron losses before steel going into use
ironlossesbeforeusephase[region]=
irontotrequired[region]-steelprodtot[region]-ironfoundryprod[region]-circscrapratiofoundry[region]*ironfoundryprod[region],
region=1 to nregion;

!cumulative iron losses before steel going into use
cumironlossesbeforeusephase[region]=
INTEG(ironlossesbeforeusephase[region],0),
region=1 to nregion;

!worldwide iron losses before steel going into use
worldironlossesbeforeusephase=LSUM(region=1 to nregion, ironlossesbeforeusephase[region]);

!cumulative worldwide iron losses before steel going into use
cumworldironlossesbeforeusephase=LSUM(region=1 to nregion, cumironlossesbeforeusephase[region]);

!CAPACITY OF VARIOUS PRODUCTION ROUTES VIA SIMPLE VINTAGE MODEL

!Capacity required
capacity[technologyfut,region]=steelprod[technologyfut,region],
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!New primary capacity build in year x
capacitynew[technologyfut,region]= SWITCH((capacity[technologyfut,region]-LAST(calccapacity[technologyfut,region],capacity[technologyfut,region])+capacitydepr[technologyfut,region])<0 ? 0
ELSE (capacity[technologyfut,region]-LAST(calccapacity[technologyfut,region],capacity[technologyfut,region])+capacitydepr[technologyfut,region])),
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Primary capacity depreciated in year x
capacitydepr[technologyfut,region]=SWITCH(t<1902 ? 0, (t-t.min)<(capacitylifetime-10) ?
capacity[technologyfut,region](1900)/(capacitylifetime+7),
(t-t.min)<(capacitylifetime+10)? LSUM(depr = 0
to 20, 1/21*NLAST(capacitynew[technologyfut,region],capacitylifetime + (depr-10),0)) +
MAX(0,capacity[technologyfut,region](1900)/(capacitylifetime+7))
ELSE LSUM(depr = 0 to 20,
1/21*NLAST(capacitynew[technologyfut,region],capacitylifetime + (depr-10),0))),
technologyfut=1 to ntechnologyfut,
```

```
region= 1 to nregion;

!Real capacity
calccapacity[technologyfut,region]=LAST(calccapacity[technologyfut,region],capacity[technologyfut,region])+capacitynew[technologyfut,region]-capacitydepr[technologyfut,region],
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!ENERGY USE

!Energy efficiency indicator compared to reference level
eei[typeofenergy,technologyfut,region]=SWITCH(t>1960 ? LAST(eei[typeofenergy,technologyfut,region],eeiref[typeofenergy,technologyfut,region])*
eeiimpr[typeofenergy,technologyfut,region],
ELSE eeiref[typeofenergy,technologyfut,region]),
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Specific energy use
sectechnology[typeofenergy,technologyfut,region]=eei[typeofenergy,technologyfut,region]*sectechnologyref[typeofenergy,technologyfut,region],
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Energy use of newly installed production
encapacitynew[typeofenergy,technologyfut,region]=capacitynew[technologyfut,region]*sectechnology[typeofenergy,technologyfut,region],
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Energy use of initial production in 1900
encapacity_ini[typeofenergy,technologyfut,region]=capacity[technologyfut,region]*sectechnology[typeofenergy,technologyfut,region],
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Energy use of capacity depreciated in year x
encapacitydepr[typeofenergy,technologyfut,region]=SWITCH(t<1902 ? 0, (t-t.min)<(capacitylifetime-10) ?
encapacity_ini[typeofenergy,technologyfut,region](1900)/(capacitylifetime+7),
(t-t.min)<(capacitylifetime+10) ? LSUM(depr = 0
to 20, 1/21*NLAST(encapacitynew[typeofenergy,technologyfut,region],capacitylifetime + (depr-10),0)) +
MAX(0,encapacity_ini[typeofenergy,technologyfut,region](1900)/(capacitylifetime+7))
ELSE LSUM(depr = 0 to 20,
1/21*NLAST(encapacitynew[typeofenergy,technologyfut,region],capacitylifetime + (depr-10),0))),
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
```

```
region=1 to nregion;

!Energy use of real capacity
calcencapacity[typeofenergy,technologyfut,region]=
LAST(calcencapacity[typeofenergy,technologyfut,region],encapacity_ini[typeofenergy,technologyfut,region])
+encapacitynew[typeofenergy,technologyfut,region]-encapacitydepr[typeofenergy,technologyfut,region],
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Derived specific energy use of capacity
derivedsectechnology[typeofenergy,technologyfut,region]=SWITCH (calccapacity[technologyfut,region]=0 ? 0
ELSE calcencapacity[typeofenergy,technologyfut,region]/calccapacity[technologyfut,region]),
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Real energy use of capacity
encapacity[typeofenergy,technologyfut,region]=derivedsectechnology[typeofenergy,technologyfut,region]
*capacity[technologyfut,region],
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Energy use per region per type of energy
entype[typeofenergy,region]=LSUM(technologyfut=1 to ntechnologyfut, encapacity[typeofenergy,technologyfut,region]),
typeofenergy=1 to ntypeofenergy,
region=1 to nregion;

!Total primary energy use per region
entotal[region]=entype[1,region]+entype[2,region]/electricityprodeff[region],
region=1 to nregion;

!Total worldwide energy use per type of energy
worldentype[typeofenergy]=LSUM(region=1 to nregion, entype[typeofenergy,region]),
typeofenergy=1 to ntypeofenergy;

!Total worldwide primary energy sue
worldentotal=LSUM(region=1 to nregion, entotal[region]);

!CO2 Emissions

!Specific CO2 emissions per fuel
co2ef[1,1,region]=0.093,
region=1 to nregion;
```

```
!Specific CO2 emissions per fuel
co2ef[1,2,region]=0.056,
region=1 to nregion;

!Specific CO2 emissions per fuel
co2ef[1,3,region]=0.056,
region=1 to nregion;

!Specific CO2 emissions per fuel
co2ef[2,technologyfut,region]=0.137,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Specific CO2 emissions per technology
sco2technology[typeofenergy,technologyfut,region]=sectechnology[typeofenergy,technologyfut,region]*co2ef[typeofenergy,technologyfut,region],
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!CO2 emissions of newly installed production
co2capacitynew[typeofenergy,technologyfut,region]=capacitynew[technologyfut,region]*sco2technology[typeofenergy,technologyfut,region],
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!CO2 emissions of initial production in 1900
co2capacity_ini[typeofenergy,technologyfut,region]=capacity[technologyfut,region]*sco2technology[typeofenergy,technologyfut,region],
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!CO2 emissions of capacity depreciated in year x
co2capacitydepr[typeofenergy,technologyfut,region]=SWITCH(t<1902 ? 0, (t-t.min)<(capacitylifetime-10) ?
co2capacity_ini[typeofenergy,technologyfut,region](1900)/(capacitylifetime+7),
(t-t.min)<(capacitylifetime+10) ? LSUM(depr = 0
to 20, 1/21*NLAST(co2capacitynew[typeofenergy,technologyfut,region],capacitylifetime + (depr-10),0)) +
MAX(0,co2capacity_ini[typeofenergy,technologyfut,region](1900)/(capacitylifetime+7))
ELSE LSUM(depr = 0 to 20,
1/21*NLAST(co2capacitynew[typeofenergy,technologyfut,region],capacitylifetime + (depr-10),0))),
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!CO2 emissions of real capacity
```

```
calcco2capacity[typeofenergy,technologyfut,region]=
LAST(calcco2capacity[typeofenergy,technologyfut,region],co2capacity_ini[typeofenergy,technologyfut,region])
+co2capacitynew[typeofenergy,technologyfut,region]-co2capacitydepr[typeofenergy,technologyfut,region],
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Derived specific CO2 emissions
derivedsco2technology[typeofenergy,technologyfut,region]=SWITCH (calccapacity[technologyfut,region]=0 ? 0
ELSE calcco2capacity[typeofenergy,technologyfut,region]/calccapacity[technologyfut,region]),
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!Real CO2 emissions
co2capacity[typeofenergy,technologyfut,region]=derivedsco2technology[typeofenergy,technologyfut,region]
*capacity[technologyfut,region],
typeofenergy=1 to ntypeofenergy,
technologyfut=1 to ntechnologyfut,
region=1 to nregion;

!CO2 emissions per region per type of energy
co2type[typeofenergy,region]=LSUM(technologyfut=1 to ntechnologyfut, co2capacity[typeofenergy,technologyfut,region]),
typeofenergy=1 to ntypeofenergy,
region=1 to nregion;

!Total CO2 emissions per region
co2total[region]=co2type[1,region]+co2type[2,region],
region=1 to nregion;

!Total worldwide CO2 emissions per type of energy
worldco2type[typeofenergy]=LSUM(region=1 to nregion, co2type[typeofenergy,region]),
typeofenergy=1 to ntypeofenergy;

!Total worldwide CO2 emissions
worldco2total=worldco2type[1]+worldco2type[2];

end;
```