# Shaping our energy system – combining European modelling expertise

Case study

How to decarbonize European steel production?

A global perspective.

KIC InnoEnergy

Energy System Analysis Agency

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# 1 Introduction

In this study, we investigate long term technology choices for steel production integrated with the energy sector aiming towards reaching global targets for climate change mitigation in a cost-optimal way. One of the major sources for global $CO_2$ emissions is iron and steel production. In 2010, European iron and steel production was responsible for 4.7 % of the total European $CO_2$ emissions, amounting to approximately 181 Tg $CO_2$ (UNFCCC, 2012). In terms of energy requirements, the share in total final energy consumption was 4.5 % for iron and steel production (European Commission, 2012). Technology development is on-going to reduce the emissions of iron and steel production (Birat et al., 2008; Birat, 2009).

Iron and steel production is intrinsically carbon intensive due to the requirement of coal in the reduction process of iron ore to iron. There are current on-going research initiatives focusing on alleviating this dependence (e.g. the European ULCOS initiative aiming to reduce the $CO_2$ emissions from steel production with 50 % compared to current best-practice). However, the implementation of these technologies is not foreseen in the short term and will also require significant investment for new production facilities (Birat et al., 2008; Birat, 2009). Furthermore, large deployments of carbon capture and storage (CCS) has been given a major role in reducing the future climate impact of steel production, but recently one of the major steel producers cancelled their plans to build a demonstration plant for CCS combined with steel production. This leaves no current initiatives where plans for implementation of CCS have been concretized (EurActiv, 2012). Hence, finding solutions that are economically and technologically viable for low-carbon steel production is becoming crucial.

# 2 Scope and scenarios

The scope of this study is to analyse future steel producing technologies and their costs. Scenarios are created to investigate both the impact of future steel demand patterns, climate mitigation and a certain technology preference.

## 2.1 Scope

In this case study, we take an integrated global approach on identifying cost-optimal pathways for low-carbon iron and steel production. The study highlights technology development on a global scale. While European production is mainly dependent on foreign resources, especially iron ore, production capacity is increasing in emerging economies. In 2010, 44 % of global crude steel production was accounted for by China. Not only resources, but also steel, and other commodities in the sector, are traded globally to large extent. In fact, the increased demand for steel in Europe during 2006-2007 was met by imports rather than by increasing domestic production. Furthermore, the economic recession in 2009 had a severe impact on European production, with reductions in production of approximately 30 %. Globally, production also stagnated, but quickly recovered in 2010. European production has not yet fully recovered (European Commission, 2012; World Steel Association, 2012).

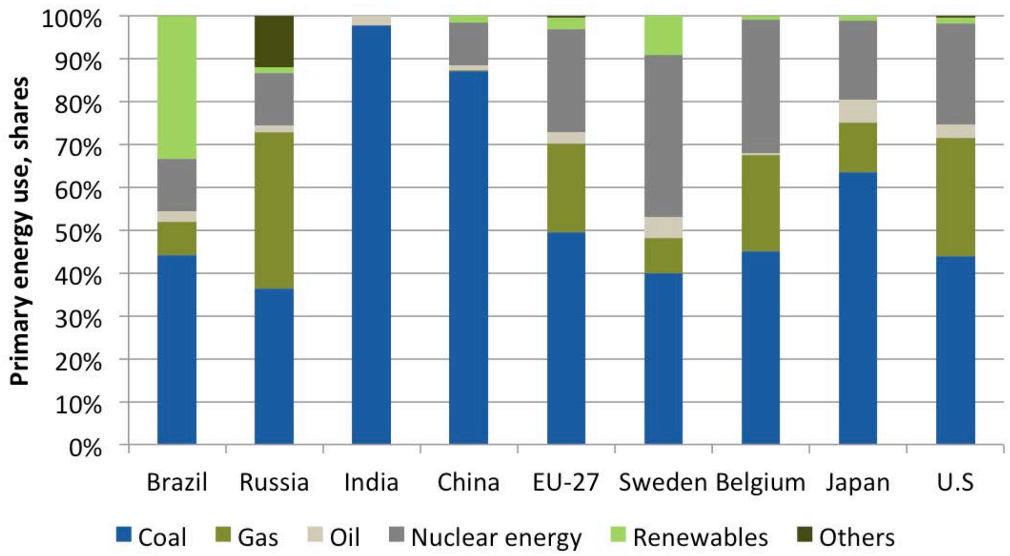


**Figure 1: Energy use of different energy carriers as share of total primary energy use in 2008. Adopted from Silveira et al. (2012).**

The majority of the recent growth in steel production has been in the Asian countries, China especially. Therefore, China is also the major consumer of energy for steel production and as can be seen in Figure 1 and Figure 2, Chinese steel production is primarily fossil based. Increasing restrictions on emissions, through for example the European Union Emission Trading System (EU ETS), are increasing costs for European producers. At the same time global competition is increasing (Silveira et al., 2012). Hence, when considering low-carbon technologies for steel production in the European setting, a global assessment is needed to show the impacts on the global market by implementing these technologies. Shifting technologies may significantly influence current trade patterns and the energy consumption and $CO_2$ emissions from production at a global scale.

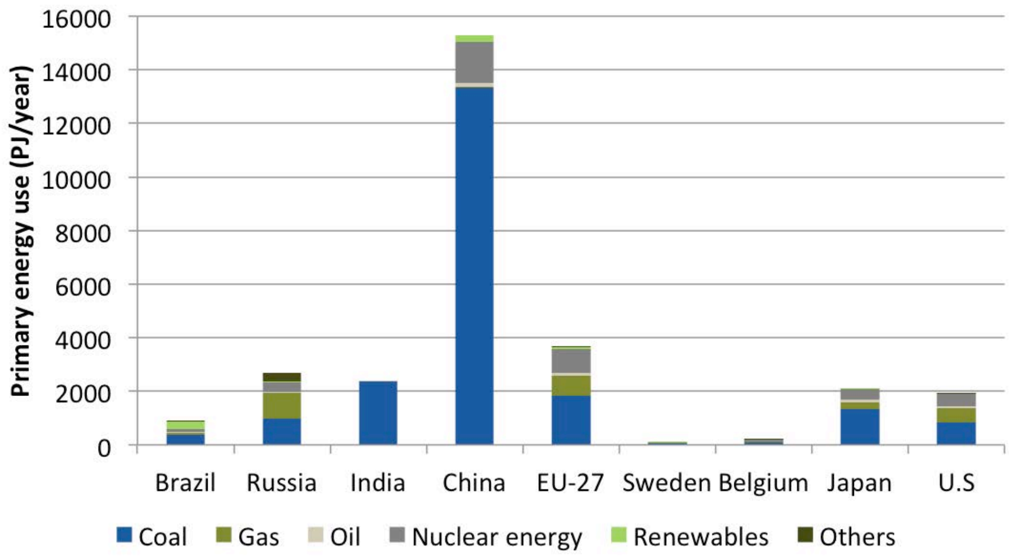


**Figure 2: Primary energy use for 2008. Adopted from Silveira et al. (2012).**

## 2.2 Two scenario groups with different steel demands

The scenarios made it possible to vary the future steel demand patterns, the ambition level for climate mitigation and technology preferences. In total, six scenarios were developed within two main groups having low and high estimates of steel demand evolution.

**Scenario group touching the limits of resources**

Historically, growth in steel demand has been approximately 3.5 % annually. If growth would continue on this level, it would mean a 100 fold increase of annual production by 2150 (Grosse, 2010). Grosse (2010) showed that such a number would not be feasible from a resource perspective and that conclusion was further verified by SAAM (see methodology for model description) showing that a global production increase of that magnitude would exceed the available reserve as well as resource of iron. In this case, SAAM was run under the assumption that all scrap becoming available would be instantly used to meet the current demand of steel. Hence, already underestimating the need for virgin material. Grosse (2010) showed that if demand growth for steel is larger than 1 % annually, the benefits from using scrap for steel production only slightly prolongs the availability of the non-renewable resource (i.e. iron ore). Hence, the incentive for secondary production does not lie within prolonging the availability of the non-renewable resource, but, as the author points out, using secondary production may increase security of raw material supply and possibly reduce pollution and climate impact of overall production. The total global available steel, counting the resource as well as the steel being in use in society, adds up to approximately 250 billion tonnes (Müller et al., 2011; U.S. Geological Survey, 2012a, 2012b). This introduces an upper limit for primary production, which is vital for the construction of plausible scenarios of future steel demand.

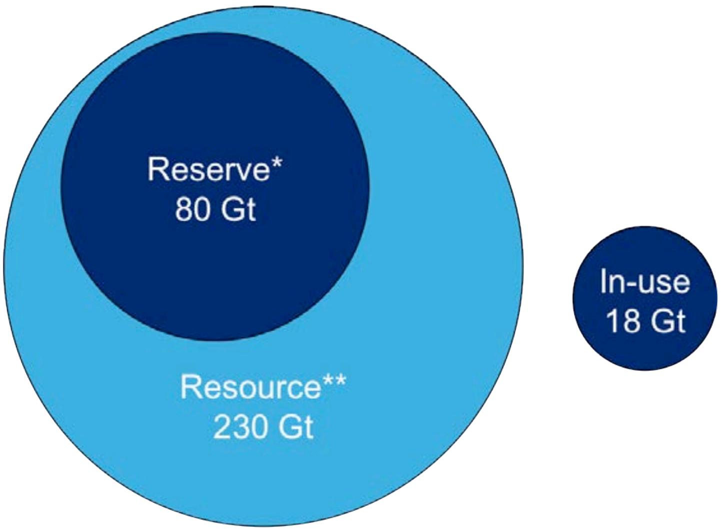


**Figure 3: Steel stock in-use in societal activities and available in reserves and as a resource (*Economically extracted or produced at the time of determination. Extraction facilities are in place and operative. **Sum of economic, marginally economic and sub-economic resources.)**

The reserves of iron ore introduce a limit on the possibilities of primary steel production (see Figure 3). The total global resource has been estimated to approximately 230 billion tonnes of iron (rather than iron ore – meaning that approximately the same amount of crude steel could be produced from the resource). However, not all of this is currently available for being extracted in an economically viable fashion using today's technology. Out of the resource, approximately 80 billion tonnes of iron could be economically extracted. This part of the resource is called the reserve (Vital and Pinto, 2009; U.S. Geological Survey, 2012a, 2012b). On top of this approximately 18 billion tonnes of iron has already been accumulated in society and this is what is called the in-use stock of iron (Müller et al., 2011).

**Scenario group with a saturated in-use steel stock**

The concept of in-use stock of steel (or sometimes also including iron products and therefore referred to as in-use stock of iron) is based on the fact that steel becomes accumulated in society after its production and stays in society as part of infrastructure, machinery, vehicles and other everyday products. When it reaches its end-of-life, the steel is either dumped in a landfill, becomes part of the obsolete stock (steel that out served its purpose, but cannot be recovered) or becomes available as scrap for use in secondary production.

Several studies have identified the tendency of countries reaching a saturation level of their in-use stock of steel per capita (Müller et al., 2011; Pauliuk et al., 2013). The saturation level seems to have occurred at levels of approximately 8 to 16 tonnes per capita for industrialized economies. This tells us something about the future evolution of steel demand and, also, due to the time lag for the use of steel in society, about the scrap available for secondary steel production. Secondary steel production is especially important for reducing the carbon intensity of steel production, since it requires much less energy in its process and can, also, the energy can be supplied as electricity which could then be produced using low-carbon technologies (Worrell et al., 2007). Scrap is essentially steel that has already served its purpose in society and is therefore available as a resource for new production. Depending on the specific area of usage, steel is accumulated in society for different durations of time (Davis et al., 2007; Grosse, 2010; Müller et al., 2011; Pauliuk et al., 2013). Müller et al. (2011) suggested that the saturation of in-use stock per capita is correlated with the level of GDP per capita of the analysed region. The authors analysed a number of industrialized economies to find that the saturation has occurred for the U.S., the U.K. and France, whereas Australia and Canada, also already industrialized economies, did not yet reach the level of saturation.

## 2.3 Scenario overview

The two main scenario groups built upon the steel demand scenario of ETSAP-TIAM, version 2010, which has a growing steel demand over the total modelling period (assumed to be constant after 2100) as well as a steel demand scenario with a growth that goes from current level to zero after 2050. The first group of scenarios had a constant steel production after 2100 of higher than 5 billion tonnes per year, touching the limit of resource availability (se further discussion in paragraph 4.2). The second had a yearly steel production of 2.5 billion tonnes of steel after 2050. The latter scenario was created inspired by results from SAAM in which useful steel in society accumulates to levels currently visible in developed countries (see further discussion in paragraph 4.2).

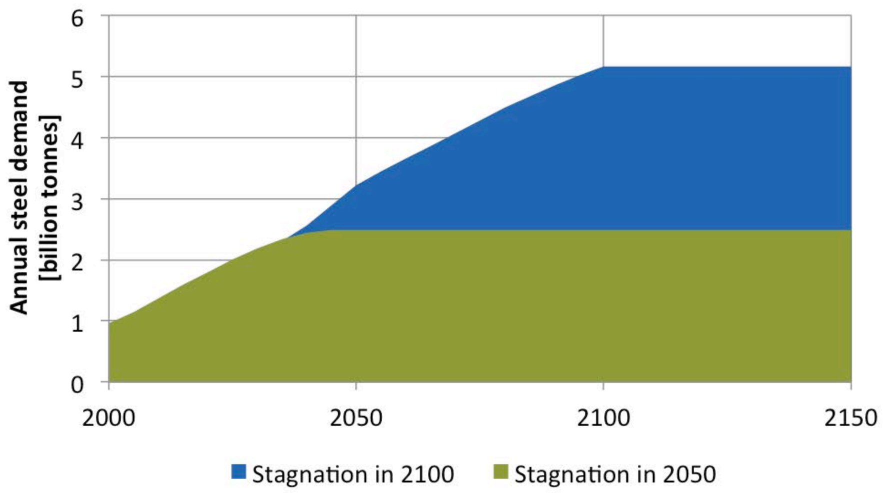


**Figure 4: Visualization of demand stagnation scenarios.**

Another dimension was added to the scenario definition by varying the level of climate ambition and restricting the technology choices by excluding an important mitigation option for the steel sector: carbon capture and storage. Table 1 shows the three variants in combination with the demand scenarios shown in Figure 4.

**Table 1: Scenario definition.**

| **Climate ambition** | ***Demand stagnation in 2100*** | ***Demand stagnation in 2050*** |
|---|---|---|
| **Reference scenario** | The reference scenario does not envisage any ambitious climate policy. Radiative forcing in 2100 is 6.7 W/m² and $CO_2$ concentration more than 600 ppm. | |
| **3.5 RF Climate** | The climate module of ETSAP-TIAM is used for these scenarios to limit the radiative forcing up to a level of 3.5 W/m² in any timeframe. | |
| **3.5 RF Climate (no CCS)** | In these scenarios, storing captured $CO_2$ is not allowed in any sector. | |

# 3 Methodology

Two models were used in the case study, the well-established global energy model *ETSAP-TIMES Integrated Assessment Model* (ETSAP-TIAM) maintained by *Energy Technology Systems Analysis Program* (ETSAP) and a *Scrap Availability Assessment Model* (SAAM), developed within the scope of the ESA[2] initiative.

A scrap availability model, SAAM, was developed to capture the scrap availability based on the demand scenarios used in ETSAP-TIAM, SAAM also give indications on the in-use stock of steel as well as the saturation levels on a global scale. ETSAP-TIAM can highlight technology development on a global scale based on cost-optimization modelling for technology options up until 2100. The ETSAP-TIAM global energy model was extended with explicit representation of steel production technologies.

The novelty of the approach is the technology detail for iron and steel production in a model traditionally used for energy technology cost-optimization and the extension of the model to take restrictions on scrap availability into account as well as saturation of in-use stock of steel.

## 3.1 SAAM: global scrap model

The primary aim of SAAM (Scrap Availability Assessment Model) was to estimate the scrap made available at each point in time. Different societal sectors accumulated steel for different lengths of time and, therefore, the scrap made available at one point in time is composed of steel that has reached its end-of-life in sectors associated with different residence times.

SAAM modelled the scrap availability annually based on estimated steel demand from 1900 – 2150. Historic demand was assumed to increased exponentially with an annual growth of 3.5 %, following Grosse's (2010) approximation for 1950 - 2007, based on the 2005 value given in the scenarios. To harmonize the data with ETSAP-TIAM, the results are given for every five years for the modelled period. The following equation was used to estimate the scrap made available at a certain point in time.

$$S_{\mathrm{t}} = \sum_{i=0}^{n} \eta_i \cdot \rho_i \cdot (1-\gamma_i) \cdot P_i, \qquad (1)$$

where $S_t$ was the scrap made available during time period $t$, $\eta_i$ was the sectoral split of steel into each product group, $i$, had in the total in-use stock of steel, $\rho_i$ was the recycling rate of the same product group, $\gamma_i$ was the fraction of the in-use steel forming obsolete stocks, and $P_i$ was the total steel produced for the time period equal to $t$ minus the average life-time, $T$, of the product group $i$. The parameters were chosen based on estimations provided by Pauliuk et al. (2013) (see Table 2). The fraction of in-use steel forming obsolete stocks was assumed to be steel used in construction under ground that would not be recovered when the structure was demolished, for example. This type of steel scrap was estimated to 10 % of the total steel produced by Pauliuk et al. (2013). The average sectoral split (calculated on the input to Pauliuk et al. (2013)'s model) was used as the global average.  The base value for the average life-time of Pauliuk et al. (2013)'s model, previously estimated by Müller et al. (2011) were used as the global average life-times for the product groups.

**Table 2: Input parameters for SAAM.**

| **Product group** | ***T*** | $\eta_i$ | $\rho_i$ **(for 2005)** |
|---|---|---|---|
| **New scrap** | 0 years | 9 % | 100 % |
| **Products** | 15 years | 5 % | 58 % |
| **Transportation** | 20 years | 40 % | 82 % |
| **Machinery** | 30 years | 15 % | 87 % |
| **Construction** | 75 years | 40 % | 82 % |

Furthermore, the recycling rates, $\rho_i$, were assumed to be gradually increasing over the whole time period rather than constant, in contrast with Pauliuk et al. (2013). The reason for this assumption was that we did not expect recycling to be as well developed at the beginning of the 20$^{th}$ century as it is today. Therefore, the recycling rates were chosen as to grow exponentially with 1 % annually during the period 1900 – 2005. During the period 2005 – 2100 the rates were chosen so that they continue growing exponentially at reduced paces for reaching 100 % in the year 2100. After 2100, the recycling rates were assumed to be equal to 100 %.

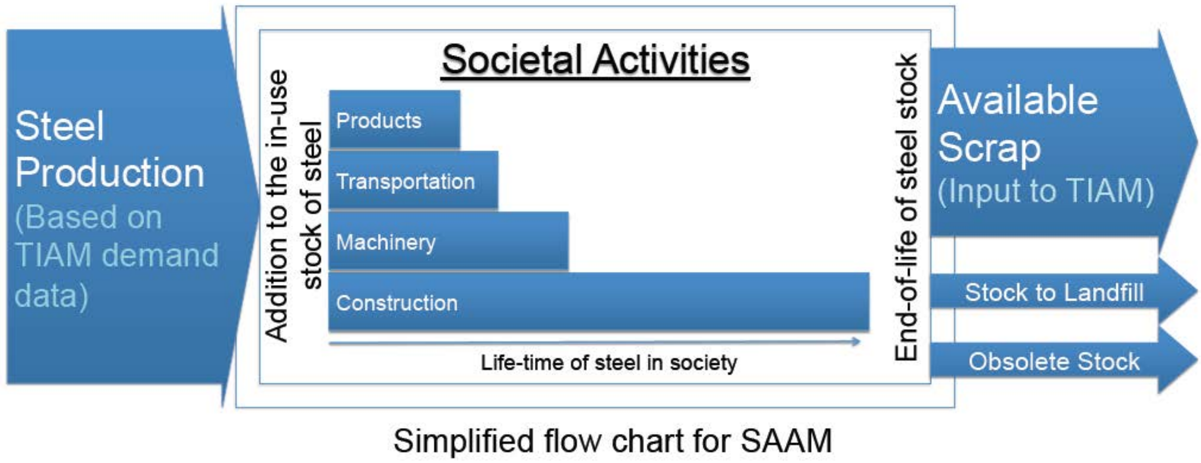


**Figure 5: Graphical representation of SAAM.**

The product category *New scrap* is the scrap from product manufacturing that never enters society. Hence, it can be recycled the same year as it arises. *Own scrap*, which is sometimes referred to as home scrap, is not modelled since it is recycled within the factory gates and is therefore included in the total output of production.

SAAM was integrated with TIAM through running the same demand scenarios as TIAM to provide the addition to the global scrap market for each time slice. The resulting global scrap market in TIAM then provided the necessary limitation of the expansion of secondary production to avoid exceeding the available scrap resource. Both SAAM and ETSAP-TIAM was run using the two demand growth scenarios for steel.

## 3.2 ETSAP-TIAM: global energy model

ETSAP-TIAM was first formalized by Loulou (2007) and Loulou and Labriet (2007) and represented the global energy system through the individual modelling of 15 global regions. It is based on the same modelling platform as TIMES PanEU and a member of the perfect foresight family of models. One of the benefits of this type of model is that it explicitly represents technologies for production, transmission and distribution of energy carriers and comprises several thousands of technologies throughout all sectors of the economy.

Except the technical and economic parameters that characterize TIMES models, ETSAP-TIAM also includes emission coefficients for three major greenhouse gases: $CO_2$, $CH_4$ and $N_2O$. Furthermore, linearized climate equations were introduced to provide the possibility of modelling the energy system in the context of global climate change mitigation targets. The flexibility of ETSAP-TIAM was even further greatened by adding multi-stage stochastic programming and a new formulation for the forcing equation compared to previous TIMES models, providing the possibility of binding each and every component of the cost objective function.

In this study, we also explicitly modelled iron and steel production to capture the interaction between iron and steel producing technologies and the global energy system (examples of four technologies for steel production that were added can be seen in Table 3).

Table 3: Example data on four steel producing processes (Based on Van Wortswinkel and Nijs, 2010).

| | | Blast Furnace PCI | Blast Furnace - TGR - with CCS | COREX | COREX with CCS |
|---|---|---|---|---|---|
| **Costs** | Overnight Capital cost, (€2010/Mt/year) | 273 | 500 | 350 | 550 |
| | Variable O&M cost (€2010/Mt) | 2 | 5 | 2 | 5 |
| | Fixed O&M cost (€2010/Mt) | 10 | 15 | 10 | 15 |
| **Inputs** | Input Hard Coal (PJ) | 6.20 | 5.22 | 27.00 | 27.00 |
| | Input Coke (PJ) | 9.30 | 5.92 | 3.1 | 3.10 |
| | Input Pellet (Mt) | 0.155 | 0.04 | 0.75 | 0.75 |
| | Input Sinter (Mt) | 1.340 | 1.54 | 0.75 | 0.75 |
| | Input Electricity (PJ) | 0.5 | 0.27 | 0.324 | 1.075 |
| | Input Oxygen (Mt) | 0.05 | 0.45 | 0.70 | 0.69 |
| **Outputs** | Output Blast Furnace Slag (Mt) | 0.25 | 0.25 | 0.30 | 0.35 |
| | Output Blast Furnace or other gases (PJ) | 3.25 | 0.70 | 10.90 | 10.9 |
| | Sinked $CO_2$ (Mt) | | 0.79 | | 0.76 |

One of the most important parameters for technology deployment in ETSAP-TIAM is the demand for each time period. The sectoral demands of each region in ETSAP-TIAM are based on a exogenous drivers provided by the general equilibrium model GEMINI-E3 (Loulou and Labriet, 2007b). The sectoral demands then induce an energy demand trough the energy intensity of a given sector. For steel production, this representation has been extended through adding steel producing technologies. However, GEMINI-E3 does not provide input on the scrap availability. It does not take resource limitations and saturation levels of in-use consumption into account either. Therefore, an additional model for scrap availability assessment (SAAM) was constructed. SAAM was used integrated with ETSAP-TIAM, see explanation below, as well as in stand-alone mode to provide further insight to issues surrounding steel demand, scrap availability as well as in-use stock of steel and resource limitations.

ETSAP-TIAM was then run with two demand growth scenarios. The first was the demand growth scenario currently used in ETSAP-TIAM. In this scenario, demand was assumed to be growing at a rate of 4.2 % annually in 2005 and then gradually decreased to 0 % in 2100. This scenario was hence named *Demand stagnation in 2100*. In the second scenario, demand was assumed to be growing at a rate of 3.5 % annually in 2005 and to then decrease linearly from 3.5 % to 0 % in the year 2050. This scenario was hence named *Demand stagnation in 2050* and was also updated with historic data on demand levels for the base year, 2005, compared with the *Demand stagnation in 2100*, currently used in ETSAP-TIAM. The two demand scenarios were then executed within three global scenarios in ETSAP-TIAM: a reference scenario, a scenario aiming to reach the 2$^{o}$C climate change target set by the IPCC (using all available technologies) and a scenario aiming to reach the the 2$^{o}$C climate change target set by the IPCC without using carbon capture and storage (CCS) technologies.

# 4 Results

The technologies used for producing steel that were integrated in ETSAP-TIAM had different characteristics in terms of energy demand, material demand, costs and $CO_2$ emissions. The group of technologies referred to as primary production were the ones based on iron ore as the materials resource. Some of these technologies can also use a limited amount of scrap to supplement the iron ore, but not exclusively. These technologies are characterized by a large energy demand per tonne of produced steel. This is because of the large requirement of energy for reducing the iron ore to iron. However, the carbon intensity of production varies depending on the type of process, especially for technologies, which are not yet commercially available. Current primary production technologies are still characterized by high carbon intensity. The group of technologies referred to as secondary production were the ones based on scrap as the materials resource. These technologies are characterized with lower energy intensity due to the fact that the scrap has already gone through the reduction process when it was first produced and also lower carbon intensity since the energy used in most cases is electricity which can be produced using low-carbon technologies (Silveira et al., 2012). Since the late 1990’s, the total steel scrap use has increased slightly from 350 million tonnes to slightly more than 450 million tonnes in 2009. The share of scrap use in total steel production has, in contrast, decreased from 44 % in 1997 to 37 % in 2009 (Bureau of International Recycling, 2010).

## 4.1 The dependence of primary production on demand growth (SAAM).

The results of SAAM showed a large requirement for primary production globally despite the assumption that all scrap made available each year would be fully used in steel production. Even for the case when demand growth was reduced to zero in 2015 almost 40% of the total demand would need to come from primary production in 2050 (the blue line in Figure 6). Furthermore, we see that aiming for reducing the long-term demand growth only fractionally reduces the requirement of primary production in 2050 (in Figure 6 long-term demand growth was varied between -2.5 % and 2.5 %).

The long-term demand growth has a more significant impact on primary production in 2100. A negative requirement for primary production was actually visible for the case of reducing short-term growth to between zero and one percent and aiming for a negative long-term growth (the third quadrant of Figure 7). The negative requirement for primary production would then indicate that society would supply steel production with secondary material to the degree of being self-sufficient without the need of virgin materials. However, reducing demand growth drastically in the short-term and aiming for negative growth in the long-term is not plausible considering the requirement of steel products in developing regions (Pauliuk et al., 2013). This means that even if we drastically reduce the growth of steel demand in the short-term, there would still be a significant requirement for primary production in 2050 and, unless we aim for negative demand growth, there would still be a requirement for primary production in 2100.

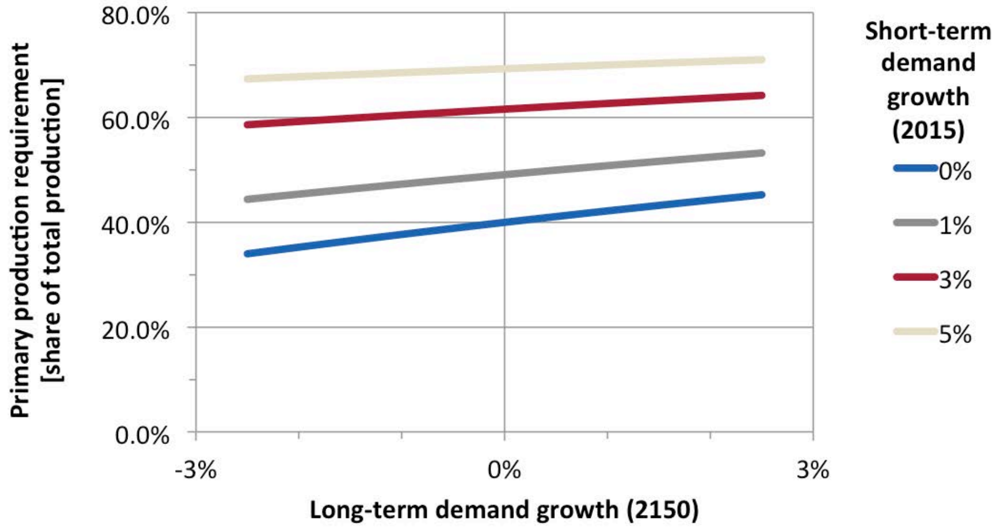


Figure 6: Primary production requirement as share of total production for varying long-term demand growth (x-axis) and varying short-term demand growth (data series), modelled for the year 2050.

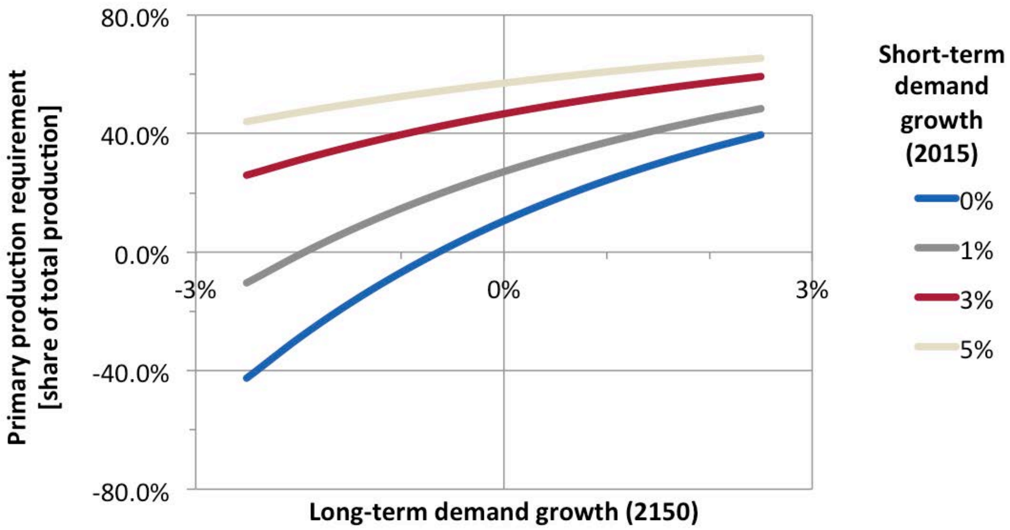


Figure 7: Primary production requirement as share of total production for varying long-term demand growth (x-axis) and varying short-term demand growth (data series), modelled for the year 2100.

## 4.2 Saturation of in-use steel stock (SAAM)

The total use of steel is limited by the total resource available and the current in-use stock of steel (as previously discussed, see Figure 3). Therefore, if a circular economy for steel is to be reached, a saturation of the in-use stock per capita at a global level has to be achieved. Furthermore, the total cumulative in-use stock may not exceed the total resource available in the long-term. The total available iron is estimated to approximately 250 Gt, taking the full resource as well as the current in-use stock into account. It should be noted that only approximately 100 Gt of these are available using current techniques.

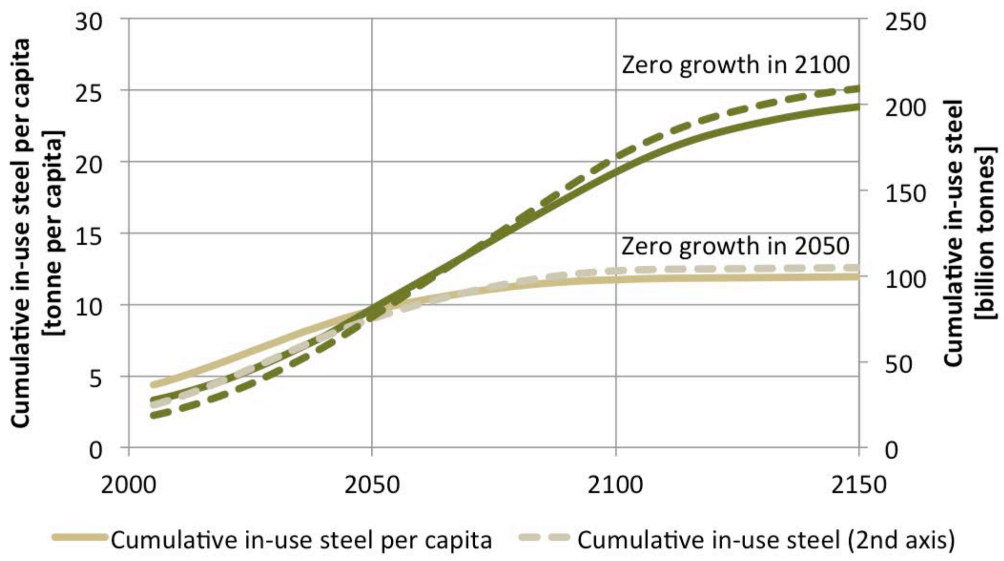


**Figure 8: Cumulative global in-use stock of steel for two demand growth scenarios: Demand stagnation in 2050 and Demand stagnation in 2100.**

SAAM was used to investigate whether the current ETSAP-TIAM scenario complies with these limitations and compared it with the *Demand stagnation in 2050* scenario. The results showed that the current ETSAP-TIAM scenario would result in an in-use stock of steel per capita of 20 tonnes per capita in 2100 and 25 tonnes per capita in 2150 (see Figure 8). These numbers are much higher than the level where the in-use steel stock per capita saturates for industrialized economies. Pauliuk et al. (2013) estimate the saturation level to be between 11 and 16 tonnes per capita and Müller et al. (2011) estimate it to be between 8 and 12 tonnes per capita. If currently emerging and developing economies would follow the same pattern as the currently industrialized economies, we would expect the global average in-use stock of steel per capita to be significantly lower than the results indicate.

Furthermore, the results showed that the ETSAP-TIAM scenario would result in a cumulative in-use stock of steel slightly above 200 billion tonnes. This number is close to the full resource potential and would require new techniques to extract iron from the earth’s crust. In contrast, the results showed that the *Demand stagnation in 2050* scenario follows previous studies much closer. That scenario results in a in-use stock of steel of approximately 12 tonnes per capita and a total cumulative in-use stock of 100 billion tonnes.

## 4.3 Technology choice (ETSAP-TIAM)

When comparing the scenarios with stagnating demand after 2100 with the scenarios with stagnating demand after 2050, it was evident that the primary production requirement was considerably larger for the first scenario group. However, the share of non-scrap material in total demand was less dependent on the scenario going from 50 to 60% in 2050 (left column) to 20 to 40% (right column) in 2100. The graphs give higher shares of “primary routes” as some amount of scrap supplements the basic oxygen steel.

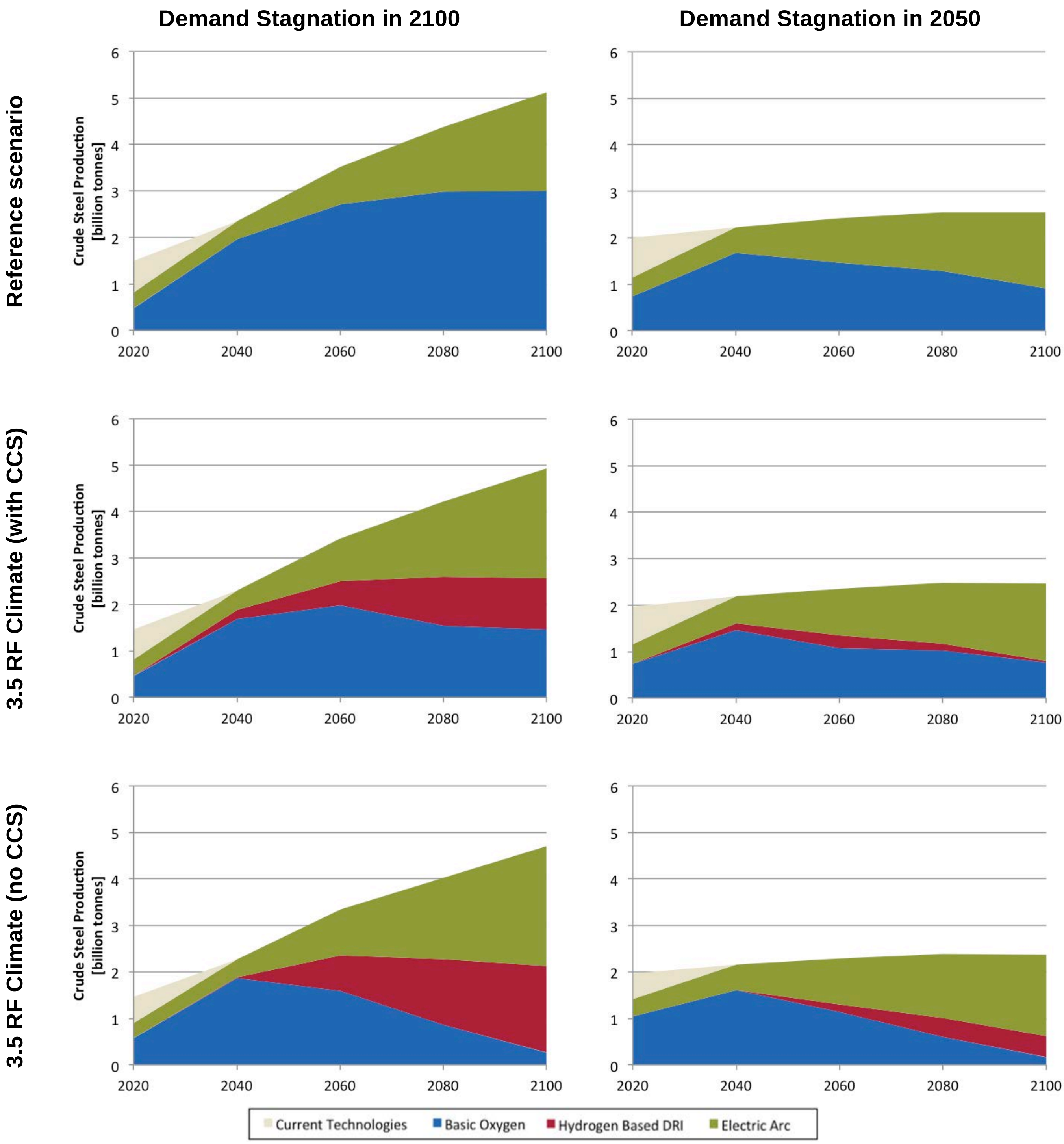


Figure 9: Future global steel production divided on technology group.

Unless steel production will stagnate earlier, half of the total demand would need to come from primary production in 2050. Primary steel disappears with a delay of more than 50 years after growth stagnation. As from 2050, scrap based steel will be produced in amounts similar to today's primary steel and a strong increase is expected afterwards.

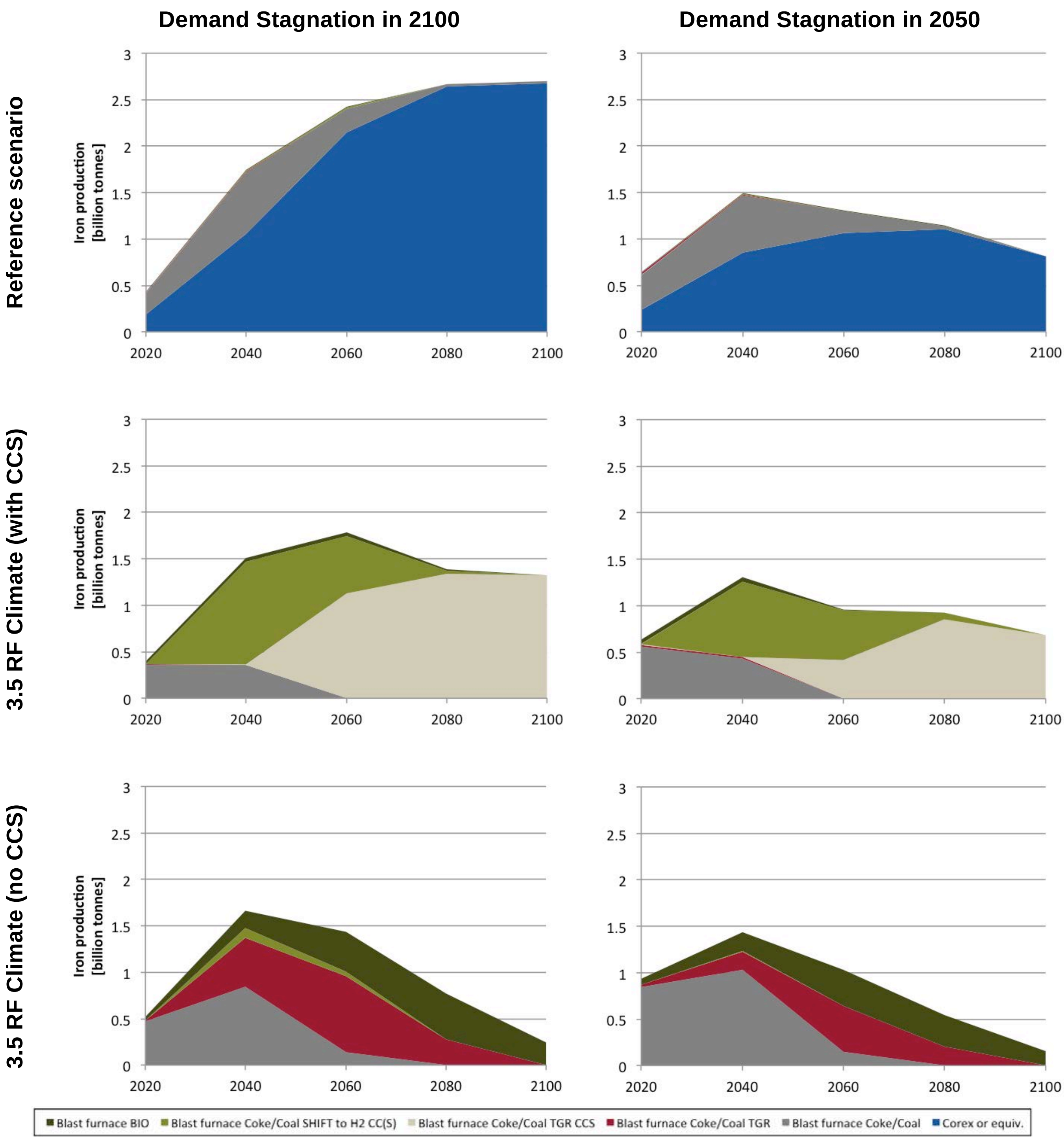


Figure 10: Future global iron production divided on technology group.

We also conclude from figure 9 that climate policy only has a minor impact on the use of steel scrap. Actually, the technology of recycling steel is economic in any case. Hydrogen based steel is a possible route for decarbonising the steel sector. The hydrogen comes from different sources like biomass and electricity. The steel sector could be a very large consumer of electricity by using hydrogen as a reduction agent.

More detail is given in figure 10 with the different technology groups producing iron. The reference scenario allows COREX technologies to produce iron with the important advantage of producing large amounts of siderurgical gases than can be used in other sectors. Typically, classic blast furnaces with coal injection are in competition with the COREX technology. The climate scenario makes steel production with CCS cost effective. It is also showing that energy efficiency does not sufficiently reduce $C0_2$ –only up to 4.1 GJ/Mton- and that completely new or different processes are required. The only alternatives are (i) new processes which are intrinsically more energy efficient and/or carbon-neutral, (ii) low carbon reducing agents fuels, and (iii) $CO_2$ capture and storage (CCS). When CCS is excluded, iron is produced via biomass or hydrogen based processes.

## 4.4 Costs and prices (ETSAP-TIAM)

Demand evolution does not have a big impact on the prices of scrap, iron and steel unless when CCS is excluded as an option. Without climate policies in place, the prices are rather constant probably because of the assumption of constant mining costs of around 80 $/ton iron ore. The price of scrap does not increase either (in real terms) and this is in line with the conclusion that there is a certain balance between production and historical production of steel.

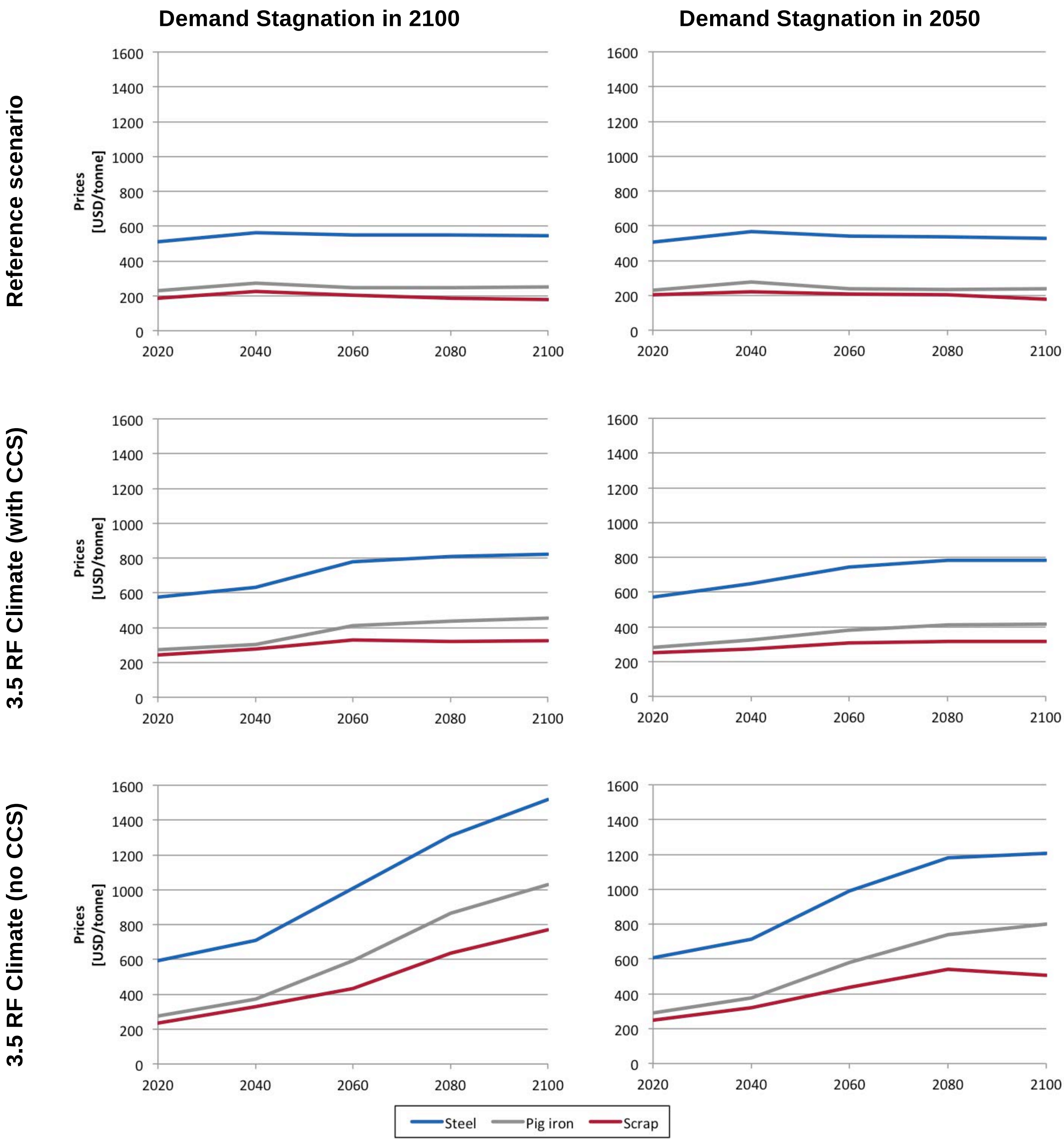


Figure 11: Commodity prices.

The climate policy to keep radiative forcing within the 3.5 $W/m^2$ limit, doubles the price of iron, makes the price of scrap go up with 50% and increases the price of steel from lower than 600 $/ton to some 800 $/ton.

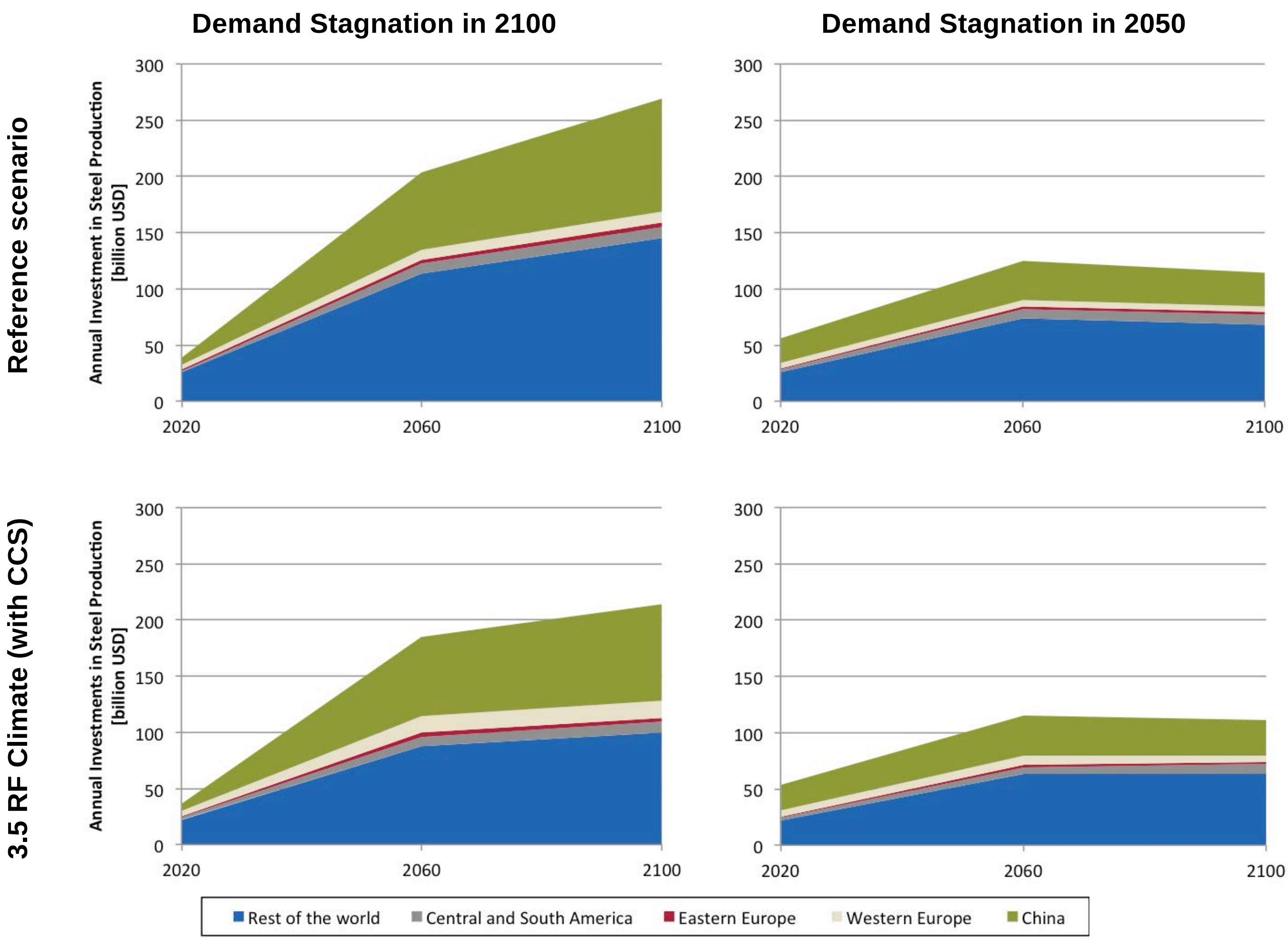


Figure 12: Investment in steel production processes for some major steel producing regions (annuities).

The highest annual investments in the iron and steel sector (figure 12) amounts to 20 B$ for EU and 100 B$ for China, when distributing lump sums over their technical lifetime. These costs are increasing as it only covers new installations. Investment costs are again plotted in figure 13 for the case of the 3.5 RF Climate scenario, but now together with other major costs like the iron ore and scrap costs. The scrap cost can be represented in two ways. The first representation “scrap cost (estimate)” is the real cost of recuperating and shredding the material. The second representation “scrap cost for user” gives the opportunity cost and it includes a scarcity rent reflecting the obligated use of more carbon intensive alternatives that would have to pay the carbon price (see figure 14). We conclude that the scrap market will have an incredible market value in the future.

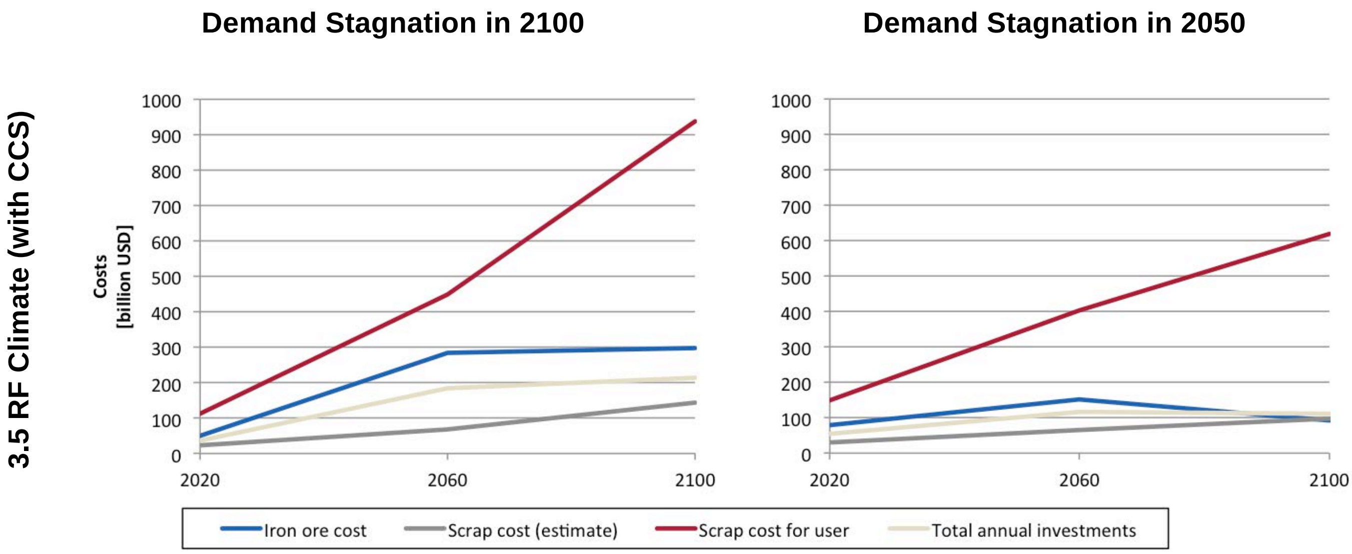


**Figure 13: Annual global costs for the 3.5 RF Climate scenario with CCS.**

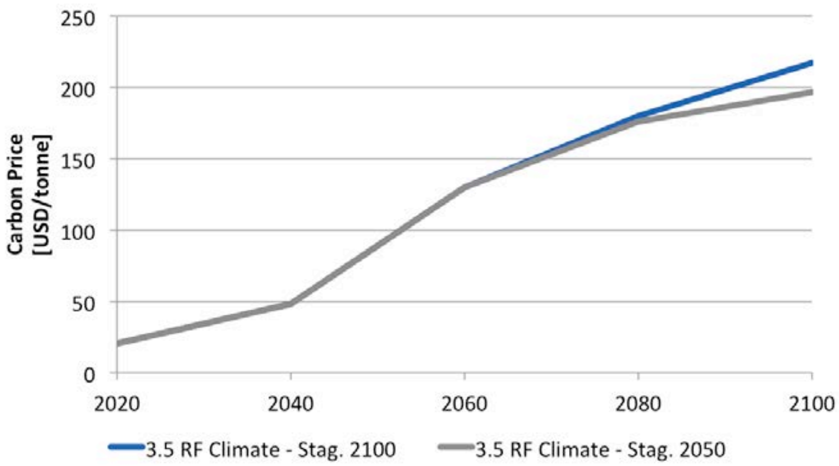


**Figure 14: Carbon price for the 3.5 RF Climate scenario with CCS.**

This discrepancy between price (cost for the user) and cost (in terms of production factors) is also visible in the decomposition of the user costs for 1 tonne of crude steel in Western Europe in 2060, under the assumption of a 3.5 W/m² climate scenario and without CCS. The cost for $CO_2$ is becoming the largest cost component for the oxygen steel. Small variations in this cost component would have a huge impact on the margins of selling steel. Electro-steel has a similar price (in the model it is equal as no distinction is made between qualities) and the price of scrap represents 75% of total costs.

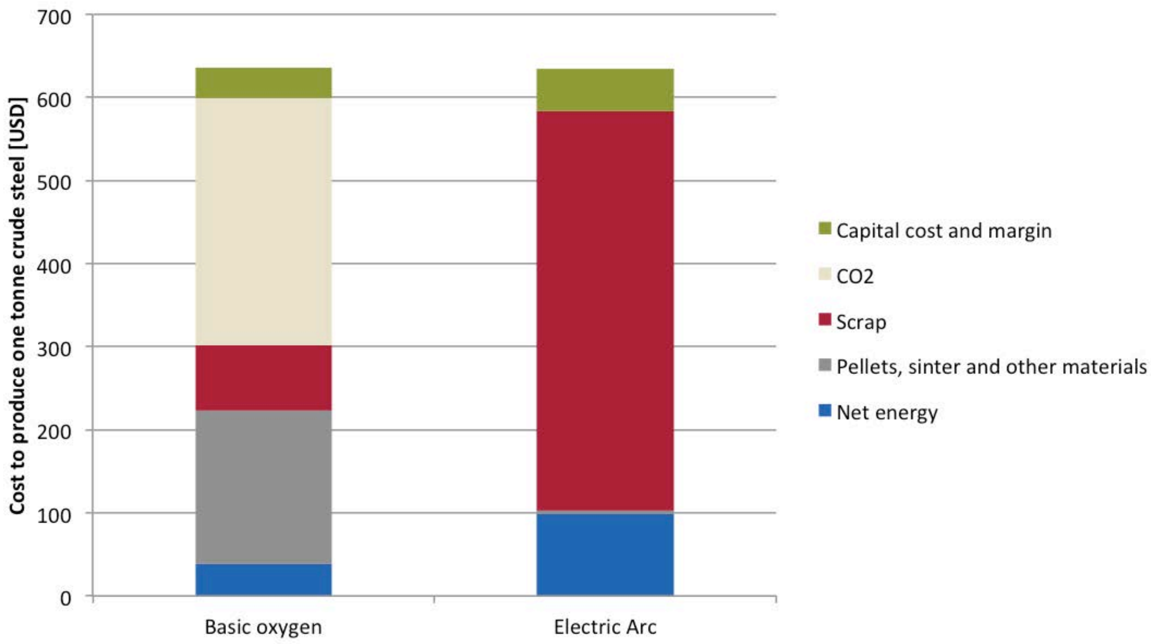


**Figure 15: User costs for 1 tonne of crude steel (Western Europe, 2060, 3.5 RF Climate scenario without CCS, demand stagnation in 2050).**

# 5 Conclusions

The scope of this study was to analyse future steel producing technologies and their costs within the context of global long term steel use and global climate mitigation. Different technical expertise is united from different ESA² partners allowing to couple model based analysis. Scenarios were created to investigate both the impact of future steel demand patterns, climate mitigation and a certain technology preference. In total, six scenarios were developed within two main groups having low and high estimates of steel demand evolution. The novelty of the approach is the technology detail for iron and steel production in a model traditionally used for energy technology cost-optimization and the extension of the model to take restrictions on scrap availability into account as well as saturation of in-use stock of steel.

Theoretically, a 90% recycling rate of steel is possible with low energy requirements and $CO_2$ emissions. However, at a global level, the requirement for primary production will be present despite using all available scrap for secondary production. Production of primary steel will globally be at least 50% in 2050 under the assumption of unchanged steel applications and corresponding lifetimes. Even if demand growth of steel would be drastically reduced, primary production would be needed due to scrap made available not being enough to meet the future steel demands.

This means that attention needs to be given to developing cleaner routes for primary production at the same time as aiming towards reducing the demand for steel in societal activities. Steel demand growth will slow down in any case in the future due to the mechanism of saturation of steel stock per capita. After 2020, growth rates of steel production in China will not be higher than 3% if it is to fulfil domestic steel demand.

Energy efficiency does not sufficiently reduce $CO_2$. Higher $CO_2$ reductions can be attained by (i) new processes which are intrinsically more energy efficient and/or carbon-neutral, (ii) low carbon reducing agents fuels, and (iii) $CO_2$ capture and storage (CCS). We also conclude that climate policy only has a minor impact on the use of steel scrap. Actually, the technology of recycling steel is economic in any case. Hydrogen based steel is a possible route for decarbonising the steel sector. The hydrogen comes from different sources like biomass and electricity. The steel sector could be a very large consumer of electricity by using hydrogen as a reduction agent.

When distributing lump sums over their technical lifetime, the highest annual investments in the iron and steel sector amounts to 20 billion USD for the EU and 100 billion dollars for China. The climate policy to keep radiative forcing within the 3.5 $W/m^2$ limit doubles the price of iron, makes the price of scrap go up with 50% and increases the price of steel from lower than 600 $/tonne to some 800 $/tonne. However, a large share of these price increases are due to carbon prices of the model and do not reflect production costs.

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