Achieving a decarbonised European steel industry in a circular economy

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Abstract

As part of the European Union’s climate commitment including the adoption of the Paris agreement, the European commission has developed a long-term strategy with the goal to reach net zero CO₂ emissions in 2050. To achieve this, a transformation of the European industry is necessary, as it represents 30% of EU’s total emissions. A major challenge will be to cut emissions in the CO₂ intensive steel industry, which is considered hard to abate. To reach the Paris agreement, deep emission cuts are necessary to occur within a decade, before cumulative emissions are too high.

Today, about 60% of all steel in the EU is produced using coke as feedstock, a process resulting in large CO₂ emissions. A new process in which hydrogen is used instead of coke is under development, with no direct CO₂ emissions as result. The implementation of such technologies can help shift the production from fossil based to renewable, with declining emissions as a result. Until now, most abatement methods are focused on the supply side, finding technical solutions that can reduce emissions. This study shows that technology can play an important role in the transformation of the steel industry but will not alone achieve the necessary reductions fast enough.

To achieve near-zero emissions in the steel industry, the solution set needs to widen to include demand side measures. The results show that circular economy principles that promote higher shares of recycled steel and reduced losses have the potential to lower total demand. This also applies for circular business models, by which incentives for higher utilisation and lifetimes of products can be created. In this report, demand-side measures are analysed using a stock-based steel demand model. It is estimated that demand-side measures can decrease the steel demand by 27% in 2050, compared to a business as usual scenario. Applying circular principles would also increase the share of recycled steel being produced from old steel scrap, a process far less CO₂ intensive than virgin production.

The findings are, that demand side measures can provide immediate deep emission cuts necessary, saving time before new technologies are implemented. The lower steel demand also helps making the transition from fossil to fossil-free steel production easier. By a combination of demand side reductions and hydrogen-DR the steel industry in Europe can reach near-zero emissions by 2050.
Preface

This master thesis was conducted at Material Economics as part of a larger project, looking at the chemical industry, the cement industry and the steel industry, also including analyses of required investments. During this degree project I was employed part time at Material Economics. I would like to thank the team that I worked in, including Cornelia Jönsson, Per Klevnäs, Stina Klingvall, Johan Haeger and Anders Åhlén for sharing their knowledge and for valuable feedback.

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Introduction

The latest report from IPCC states that urgent changes are needed to limit global warming to a level well below 2 degrees, limiting the risk of escalating climate change, with increased number of severe draughts, storms and extreme weather conditions affecting both human and natural life (Intergovernmental Panel on Climate Change (IPCC) 2018). While the urgency of cutting CO₂ emissions seems to increase with each research update, the overall goal to limit climate change and heavily reducing emissions is widely accepted in the EU. With the Paris agreement the European economy has committed to ambitious climate targets limiting temperature increase to well below two degrees. To get there the European Commission has adopted a strategic long term climate vision of a net zero emission economy in 2050, but how to get there is an on-going debate without clear solutions (Eurostat 2018; European Commission 2018).

Attempts have been made to show possible ways forward, moving the European economy towards established climate goals. These roadmaps have mainly focused on energy efficiency and developing renewable energy sources as a mean of reducing emissions (European Commission 2011). This follows the same pattern of the development of solutions that has been seen in the buildings sector and in power production (Material Economics 2018). Strategies of this kind have large potential to reduce CO₂ emissions and have been proven effective. Since 2005, energy efficiency has improved by nearly 20% in the EU (Eurostat 2017). However, no ways to achieve the deep cuts necessary in heavy industry while keeping the production in Europe has been shown so far. According to a roadmap developed by the European Commission, 25% of all remaining emissions in 2050 will come from the industry (European Commission 2011).

In 2015, emissions from European industry constituted 20% of total emissions. The steel industry, being one of the most carbon intensive industries, accounted for 5% the EU’s total emissions (The European Steel Association (EUROFER) 2013; European Environment Agency 2018b). Looking to 2050, the European Economy is estimated to grow by 50% (European Commission 2012). With the same materials use as today the steel demand is expected to increase by 32% (The European Steel Association (EUROFER) 2013). With no major changes in steel production or in the way steel is used, a higher economic activity increasing the steel production is likely to lead to an increase of already high emission levels.

So far, the focus has been on developing clean production processes such as moving from fossil fuels towards renewable, increasing energy efficiency and decarbonising the power sector. These measures all have great potential and are necessary to achieve established climate goals, but evidently, they are not enough to eliminate all emissions. This is especially true for the steel industry. When making steel, fossil carbon is part of the process chemistry, which result in large emissions even with zero-carbon electricity. With focus solely on the supply side causes of emissions (the production of materials), great opportunities are missed.

Up to date, the climate debate tends to focus heavily on annual emissions and how future levels can be decreased, but cumulative emissions are as important as annual in assessing current trends and actions needed. Because of the long lifetime of CO₂ in the atmosphere, concentrations build up over time and decreases slowly, even with decreasing annual emissions. This means that atmospheric CO₂ concentrations will continue to rise even when annual emissions are declining. The remaining carbon budget is a way to measure the amount of anthropogenic CO₂ emissions that can be released until net zero emissions are reached, keeping atmospheric CO₂ levels under a certain limit. To achieve the well below 2 degrees goal, it is estimated that the remaining carbon budget is between 420-570 Gt CO₂ worldwide (Intergovernmental Panel on Climate Change (IPCC) 2018). The development of new clean technologies takes long time and effects of such solutions are not likely to be seen within the next 10-20 years. Therefore, the need for actions and solutions that cut emissions today, and not in the future, is urgent.
By shifting focus to include demand side measures, the solution set can be widened. A circular economy has the potential to improve how efficiently we are using materials, increasing the reuse and recycling of materials and improving the sharing of products and services (Material Economics 2018). By finding ways to deliver the same service with less material, the total steel demand will decrease leading to less CO₂ emissions from the industry. Combining ‘traditional’ climate abatement strategies such as zero-carbon energy, with demand side methods could help to save us time and to reduce emissions independent of production improvements.

**Aims and objectives**

The aim of this study is to investigate how the steel industry in Europe can reach net-zero CO₂ emissions, or close to, in 2050 with a maintained European steel production, and what role circular economy principles could play in this transition. The report can be said to contain two main parts as both supply side and demand side measures are investigated. Their potential to mitigate emissions will be modelled and evaluated.

To examine the potential effects of supply side measures, new technologies that have the potential to reduce CO₂ emissions in steel production will be investigated and modelled, including an increased process efficiency of today’s processes as well as a shift towards a fossil free power production. The modelling will be done by back tracking the steel production, originating from a decarbonised steel industry in 2050. Circular economy as a concept will be examined and coupled to the steel industry. The future steel demand in the EU is modelled using a forecasting method and is built upon previous forecasting done by the Swedish consultancy Material Economics.

The results from the modelling of demand and supply side measures will be compared, with the objective to see each measure’s role in reaching net zero emissions in 2050. Furthermore, discussions will be carried out on whether a combination of measures is necessary or if some solutions have the potential to cut emissions alone.

**Methodology**

**Supporting data and models**

The results in this study are based on a model created in Microsoft Excel. Existing literature has been used to build an understanding of the steel industry and related topics, such as circular economy and climate goals. Literature has been used to find the data on which the models are built, such as emission data, product volumes and electricity usage. The literatures that have been used are scientific articles, scientific and commercial reports, and product brochures.

To be able to make a forecast of future steel demand in Europe an existing model has been used and altered to serve the purpose of this study. The model used is a steel stock model created by Material Economics (Material Economics 2018). This model has been used as a demand projection for a business as usual scenario, which then has been altered to achieve a circular pathway with a lower demand. The steel stock model incorporates factors such as population growth, available steel scrap, contamination of steel scrap and stock saturation levels, which are all discussed in more detail below. The model is based on a value chain perspective, therefore modelling the steel demand from trends in the steel sector’s major value chains.

**Modelling of future CO₂ emissions**

To model the future CO₂ emissions until 2050, forecasting has been necessary to project trends in steel making volumes. The forecasting modelling has been used to make predictions of steel demand in Europe until 2050, by adding circularity leavers on top of already existing business as usual projections. Understanding future steel demand is highly relevant since the CO₂ emissions are directly linked to the steel production volumes.
With the purpose of this study being to develop a pathway that realises zero, or close to zero, CO\textsubscript{2} emissions by 2050, this end-year naturally becomes the starting point in the modelling. By knowing the desired outcome but not the way to get there, the modelling can be said to originate from a set endpoint in 2050. It is therefore important to understand that this modelling method and the result it provides is not to be seen as a forecast, predicting real life trends, but rather a way of showing a scenario of what is needed to reach a desired result.

The projected steel demand serves as the base in the model. The time frame is divided into 5-year periods, giving the steel demand for every fifth year, starting in 2015. The demand is the foundation of the CO\textsubscript{2} calculations as emission factors per tonne produced steel are used. Different combinations of demand levels, shares of the production routes and emission factors for the production routes are used to create and calculate the different scenarios. With the different inputs of production volumes together with emission factors and production shares, annual and cumulative emissions can be calculated.

The emissions are calculated by multiplying the volumes produced by each route with corresponding emission factors. To create a scenario that reaches close to net zero the BF-BOF production is entirely replaced by hydrogen-DR and EAF production because these are the routes with almost no emissions. The circular demand forecast serves as the basis for production volumes. Hydrogen-DR stands for 30\% of the total production and EAF for 70\%.

**Delimitations and methodology reflection**

This study is limited to modelling several different scenarios for future steel production in Europe and the resulting CO\textsubscript{2} emissions. Therefore, no analysis of costs and investments has been made, nor does this study include an analysis on policies and regulations to enable this necessary change. The projections of future demand volumes do not take into account that steel is traded on a global market and that changes in the levels of export or imports of steel may occur in the future. This study is limited to modelling only one of several low emission steel production technologies currently under development. Hydrogen-DR has been chosen as it is considered the most promising one.

The steel stock model developed by Material Economics has been used as a basis for future demand projections for several reasons. Firstly, it is a more robust model that is built on a stock approach discussed below, compared to other projections that are mainly built on growth opportunities for steel companies. Secondly, it gives the opportunity to alter different leavers and enabling the demand to be projected for a circular scenario. As this study was conducted at Material Economics it was also natural to use the forecast model created in-house.

By starting the modelling from 2015 there is a risk that the reality looks different when this study is finished, compared to the modelled results for 2020. However, the changes in the first modelled 5-year period are small and within historical variations seen in the last 10 years (The European Steel Association (EUROFER) 2018). The introduction and changes in rates of production routes is hard to predict. By using information from companies that develop hydrogen-DR technologies estimates have been used. The speed of the implementation of new routes is not to be considered as a forecast, but a possible development. Again, this study does not try to forecast the future but instead intends to show a possible way forward.

**Background**

**The European steel industry**

The European steel industry is one of the major industries in Europe. It supports nearly 2.5 million jobs, of which 320 thousand are direct employments, and it creates more than 20 billion gross value added to the European economy. In the European Union there are about 500 production sites that
together produces nearly 170 Mt of crude steel annually. The steel industry took a great hit during the 2008 crisis and has not fully recovered to pre-crisis production levels, with today’s production being 20% lower, a level that has been steady for the last ten years. Meanwhile, the European steel industry has seen a substantial rise in global competition, with China alone accounting for more than 50% of the world’s steel production (The European Steel Association (EUROFER) 2018).

In the production of steel, high temperatures are needed, making it a highly energy intensive industry. Electricity could be used to achieve the needed temperatures to some extent, but for the dominant production process, coke derived from coal is used. The coke is used to obtain the high temperature heat but also as feedstock in the processing of iron ore, a process being described more in depth in the next section. With today’s production relying heavily on the use of fossil feedstock, it is inevitable that the steel industry stands for large CO₂ emissions (McKinsey 2018).

The annual production of 170 Mt steel results in the release of 220 Mt CO₂, equalling 5% of Europe’s total emissions (The European Steel Association (EUROFER) 2013; European Environment Agency 2018a). As one of the most energy intensive and fossil dependent industries in Europe, it accounts for 41% of the emissions from all heavy industries in Europe (Material Economics 2018). With the rise of climate change in the European agenda, efforts have been made to reduce emissions from steel making. Compared to 1990, annual emissions have decreased by 83 Mt CO₂ or by 25%, partially due to efficiency improvements of the same type as has been seen in the energy and housing sectors during the last decade. Even though streamlining the production from an energy perspective has had an impact, the majority of the seen decrease comes from smaller production volumes today compared with 1990’s levels (The European Steel Association (EUROFER) 2013; European Environment Agency 2018a).

Two different steel making processes serve as main production routes in the European economy, and they distinguish by using different feedstock. The primary steel production accounts for 61% of all steel produced today and is the production route in which virgin steel in produced from iron ore. This primary steel tends to be of higher quality and can be produced to meet all types of quality requirements. The remaining 39% of the steel produced comes from secondary steel production, in which steel scrap is used as feedstock and re-melted to form new steel. Because it uses steel scrap, secondary steel quality is highly dependent on the sort and quality of the steel scrap used (The European Steel Association (EUROFER) 2018; McKinsey 2018; Material Economics 2018). Primary and secondary steel production differ in most aspects, from feedstock to end product, since secondary steel making is a way to recycle steel. To form virgin steel, iron ore is oxidised and melted to get pure iron, which is further processed to attain steel. In secondary production the feedstock itself is already steel but in the form of steel scrap. Because of this, the procedure is simpler and is rather a way of reforming the steel by re-melting it.

**Primary steel production**

Virgin steel is produced by a procedure called blast furnace-blast oxygen furnace or BF-BOF. This procedure builds on the same principles that have been used for centuries in steel making with few modifications, where iron ore and coal are used as main feedstock. The coke serves two purposes in this procedure as it acts as a reducing agent as well as a fuel, providing the high-temperature heat that is needed to melt the iron ore. The coke is transformed in the blast furnace into carbon monoxide (CO) through an exothermic reaction producing heat. The heat is used to melt the iron ore while the CO acts to reduce the iron ore (Fe₂O₃). By reducing the iron ore, the oxygen is removed, leaving pure iron (Fe) and CO₂. The melted iron will then be processed further depending on the purpose and type of steel produced. This includes casting the steel, forging and mixing it with certain alloys to give the steel its specific characteristics (McKinsey 2018; Material Economics 2018).

Not surprisingly, the use of coke in primary steel production leads to large CO₂ emissions. To produce one tonne steel, 0.77 tonnes of coke is used, resulting in a total of 1.73 tonnes direct CO₂ emissions from the reducing process and the heat production (World Coal Association 2018; Zuliani, Scipolo,
and Born 2009). Of this, 40% of the CO₂ emissions are measured to come from coke used in the reducing process with the remainder from coke used as fuel to provide a high-temperature heat (McKinsey 2018). In addition, the further downstream processing comes with carbon emission of 0.11 tonnes per tonne steel (Milford et al. 2012).

Even though coke is used as the primary energy source in the process, electricity is still needed to some extent in both the main procedure and in downstream processing. The total electricity need adds up to 0.29 MWh per tonne steel, equally split between direct and downstream usage (Milford et al. 2012). With an average CO₂ intensity in 2015 of 0.27 tonnes per MWh produced, this results in a total of 0.08 tonnes CO₂ per tonne steel (European Commission 2011). To show the whole picture, all the direct, indirect and downstream emissions from the primary production through the BOF-route need to be added up, resulting in total emissions of 1.92 tonnes per tonne steel produced. As the indirect emissions from the electricity production only accounts for 4% of the total emissions, the carbon intensity of the electricity has little effect on the overall emissions.

As in the energy sector much focus has been on increasing efficiency, and current estimates suggest that an additional efficiency potential of 15% can be reached with the use of the best technologies available (Milford et al. 2013). Since the 90’s, much effort has already been put into streamlining the production and improving efficiency, but the effect is modest and not close to the levels needed for reaching the high targets of the Paris agreement. Between 1990 and 2010, emissions decreased from 1.97 to 1.88 tonnes CO₂ per tonne steel, resulting in an efficiency improvement of 4% in 20 years (The Boston Consulting Group 2013).

Upgrading the European steel production with the newest technologies as a means of reducing emissions requires large investments. New BF-BOF plants are estimated to come with an investment cost of 442 EUR per tonne steel capacity. A somewhat cheaper option is to retrofit existing plants, upgrading them with the newest technology. This would imply an investment of 170 EUR per tonne steel capacity (The Boston Consulting Group 2013). It is important to note that these investments would be made prior to the estimated technical lifetime of existing plants, which can be more than 20 years, adding these investments on top of primary investments. Therefore, it is likely that some of these investments will be put to the future until the lifetime is reached, to avoid stranded assets (Vogl, Åhman, and Nilsson 2018).

### Secondary steel production

Producing steel from collected scrap takes a more straightforward approach compared to virgin steel making. The secondary steel is produced by re-melting steel scrap in electric arc furnaces (EAF). The high temperature heat required comes from electricity, as there is no need to oxidise the melted scrap as with iron ore in primary steel production. Because the steel scrap is collected from multiple sources of varying kinds and qualities the purity of the steel feedstock varies. Some contaminants that come with scrap are hard to avoid or remove, such as copper or other minerals used in alloys. The quality of secondary steel is therefore highly dependent on the steel scrap and tend to be of lower quality than primary steel, due to contaminants that are hard to remove (McKinsey 2018).

In the secondary steel production, no fossil feedstock or fossil fuels are used as in the primary BF-BOF production. Instead it is a completely electrified process, making the carbon emissions associated with the production dependent of the carbon emission intensity of the electricity used. The direct electricity usage in secondary production is 0.5 MWh per tonne steel (Hybrit 2018; Li et al. 2018; Steelonthenet 2018). As with the downstream processing of primary steel, the secondary steel production is assumed to have the same downstream electricity intensity of 0.15 MWh per tonne steel (Milford et al. 2012). Overall the electricity consumption for producing one tonne of secondary steel is 0.63, resulting in 0.17 tonnes CO₂ per tonne steel produced with today’s electricity mix (0.27 tonnes CO₂ per MWh) (European Commission 2011).
However, even though the electric arc furnace does not make use of a fossil feedstock there are small carbon emissions from the process itself. These emissions come from the graphite electrodes that are used in electric arc furnaces and are estimated to be 0.01 tonnes of CO$_2$ per tonne steel (Vogl, Ahman, and Nilsson 2018). Direct emissions from downstream processing are assumed to be the same as for virgin steel, adding another 0.11 tonne CO$_2$ per tonne steel (Milford et al. 2012). In total direct and indirect emissions for secondary steel production is 0.33 tonnes of CO$_2$ per tonne steel produced with today’s electricity mix.

### Steel stock and future steel demand in the EU

Steel is used all over the world in a wide range of areas. About half of all steel produced is used in construction, such as infrastructure and housing. 21% is used for transport, 15% in mechanical engineering and the remainder in various appliances and products (The European Steel Association (EUROFER) 2018). Most of these services and products have long lifespans, meaning that the steel produced today will be locked in for years before being reused or scrapped. Hence, unlike other materials with short lifespans, the amount of steel in the world is much higher than the annual production, which only constitutes a small share of the total amount of steel in use at any time. The benefits and services that steel supports in the society is therefore related to the total amount of steel being used, the steel stock, enabling housing, infrastructure, transportation and more (Material Economics 2018; Pauliuk, Wang, and Müller 2013).

Urbanisation and industrialisation come with large investments in steel dependent sectors, such as construction, infrastructure, machinery and transportation, making this type of development major drivers of steel demand, further increasing the total steel stock by adding more steel to the economy. This aligns with the fact that emerging economies, building up their steel stock as urbanisation takes place, mainly drives global growth in steel demand. In mature economies on the other hand, such as northern Europe and the United states, the trend of an increasing steel stock has subsided as national steel stocks has saturated at a level of 11-14 tonnes steel per capita. Therefore, the steel demand in mature economies is mainly driven by a need to maintain the existing steel stock by replacing old structures and products. However, growing economies still have large unmet demands with stock levels ranging from 5 tonnes per person in China, to 1 tonne per person in India and Africa. Even countries in the EU have smaller steel stocks that are increasing rapidly, such as Portugal, Poland and Spain at 6-12 tonnes per capita. The European average is estimated to 11.08 tonnes per capita (Pauliuk, Wang, and Müller 2013; Graedel 2010; Material Economics 2018).

On average, the lifetime of steel products is 40 years, meaning that steel that was produced and entered the steel stock 40 years ago will now fall out of the stock as scrap (The European Steel Association (EUROFER) 2016). Therefore, new steel is added to the stock every year, and old steel is scrap falling out. As discussed above, the steel scrap can be used to produce new steel, with less CO$_2$ emissions per tonne, through secondary EAF production. Unfortunately, not all scrap is collected, resulting in a share of less than 80% of all scrap being recycled (Allwood et al. 2012; Material Economics 2018).

Predicting and modelling future demand of materials is difficult. A common method in materials forecasting is to extrapolate historic growth rates or to link production volumes to GDP as an attempt to predict production flows. These flow-based models may be useful for demand projections of some materials but are less suitable for a material such as steel. Flow-based models are built on the assumption that annual production equals the service and value that the material provides. Because of the long lifetimes of steel products and services such as infrastructure, housing and transportation steel production the case looks different for steel. The need for an increased level of steel services might be low, suggesting a lower future demand. But this neglects the fact that the steel stock needs to be maintained as to preserve the level of service in the society (Pauliuk, Wang, and Müller 2013).

With saturating steel stocks, the need to replace products and structures will constitute the bigger share of the total steel demand, because the demand to add more steel to the economy through new products and services will decrease. The EU population is expected to flatten until 2050, and steel stock levels
are approaching a saturation point with today’s level being close to 12 tonnes per capita. When the saturation point is reached, the steel demand will be driven almost entirely by the need to replace structures, products and services. Therefore, the actual demand is not only dependent on increasing markets and investments, but also highly dependent of the need to replace steel ‘falling out’ the stock (Pauliuk, Wang, and Müller 2013).

To estimate future steel demand a stock-based approach is needed that models the current stock levels in the economy combined with likely saturation levels. This modelling approach has been adapted in Material Economics’ (2018) steel demand projections where the European the steel stock is set to saturate at 13.7 tonnes per capita. The model includes supply chain and use circular factors that affects demand, such as losses in production, the formation of new scrap and collection of scrap for recycling. The model also incorporates the effect of contamination and downgrading of steel by tracing the in mixing of copper in the steel stock and the limitations this entails on its use. With current trends and no major changes in steel use, the annual growth will be 0.1%. The steel stock will saturate by 2050 at a level of 13.7 tonnes steel per capita in the European Union resulting in a 20% increase in demand. This is an increase by 27 Mt to a total production of 193 Mt (see figure 1).

![Annual steel demand in a business as usual scenario](image)

**Figure 1 showing the annual steel demand from 2015-2050.**

Comparing this demand projection with the steel industry’s own forecast shows that a stock-based model gives a more modest demand in 2050. Eurofer, the European steel industry organisation, predicts the steel production to increase by 35% to an annual production of 219 Mt in 2050, assuming an annual growth rate of about 0.8% (The European Steel Association (EUROFER) 2013).

**New technologies can cut CO₂ emissions significantly**

As the European steel stock grows, so does the amount of steel scrap available as feedstock for secondary production by the EAF route, making recycled steel production likely to grow. As mentioned above, the EAF route can be almost entirely decarbonised by switching to renewable electricity sources. But even with higher scrap availability, the available scrap will not be enough to meet the increased demand that comes with a growing stock, and a large share of the steel demand will therefore have to be met by primary steel production. Unlike the EAF route, switching to renewable electricity does not help much to reduce carbon emissions in BF-BOF production, since most emissions comes from the chemical process in which coke is used to reduce the iron ore. Therefore, to reach the climate goals in 2050 new technologies are necessary.

The Paris agreement combined with national and European goals are forcing not only the steel industry, but also all industries, to transform into a net-zero world. Ranging from power production to transportation and materials production. For a zero carbon (or close to) steel industry to be realistic, some general developments will have to take place. Without a decarbonised power production, it is
impossible for Europe to reach the Paris agreement and therefore, it is assumed that all electricity is renewable by 2050 in the following modelling. It is also assumed that the decarbonisation of electricity will lead to a downstream processing of steel with zero CO₂ emissions.

Several new technologies are under development that has great potential to replace the BF-BOF route in primary production in the future, with emission factors reaching almost all the way to zero. What is needed is to find other ways of reducing the iron ore, without the need of coke or other fossil feedstocks. Hydrogen-DR (hydrogen direct reduction) is a technology that has succeeded in replacing coke as the reducing agent with hydrogen. The development of the Hydrogen-DR has advanced far and several of the major steel companies are developing their own versions in parallel (Vogl, Åhman, and Nilsson 2018). Hybrit is one example, being developed jointly by Swedish companies SSAB, LKAB and Vattenfall (Hybrit 2018). Hydrogen-DR is to date the most promising technology in producing steel without the use of fossil feedstocks.

The product from the H-DR is called direct reduced iron, or sponge iron. Unlike in primary steel production via the BF-BOF route the iron ore is not melted in the reduction process, instead the H-DR is combined with an EAF into which the sponge iron is fed for melting and further processing into steel. With hydrogen as reducing agent the resulting output is pure iron and exhaust gases containing H₂O instead of CO₂, avoiding the direct emissions from coke. Several of the individual components of the hydrogen-DR process are being used in the industry today, making it closer to commercial realisation (Hybrit 2018; Åhman et al. 2018). There are other promising technologies, such as Electrowinning, using electricity as reducing agent, but so far this process is at an early stage of development (Fischenedic et al. 2014). Hydrogen direct reduction combined with an electric arc furnace is used in this study as a fossil free primary steel production route and data is taken from the Hybrit project.

The hydrogen direct reduction route requires several times more electricity compared to primary production with BF-BOF or secondary EAF production. The direct electricity use is 1.10 MWh per tonne steel, almost double what is used in the EAF production (Åhman et al. 2018). As with the other routes, the electricity use in downstream processing is assumed to be 0.15 MWh per tonne steel. However, even more electricity is needed to produce the hydrogen used in the process, with hydrogen production alone requiring 2.38 MWh per tonne steel. Totalling an electricity use of 3.62 MWh per tonne steel, the electricity consumed equals 0.98 tonnes CO₂. The direct and downstream emissions are small, making the total emissions from hydrogen-DR production 1.09 tonne CO₂ per tonne steel.

Large-scale production through the hydrogen-DR route is estimated to become a reality within the next 20-25 years, meaning that the BF-BOF will have to continue to be the main route for primary production in the coming decades. The pilot phase for Hybrit is planned to end by 2025 after which demonstration plants will commence its production (Hybrit 2018). Current estimates suggest that investments for hydrogen-DR plants will be large, with capital investments of 574 EUR per tonne steel capacity (Vogl, Åhman, and Nilsson 2018).

Hydrogen is used as fuel in several different industrial processes, with the main usage being ammonia production. It is also used as fuel to power fuel cells in transportation, an application that is expected to grow. Today, about 7 Mt of hydrogen is consumed in the EU annually (Fraile et al. 2015). Most of the hydrogen is produced using fossil fuel resources, where natural gas is the most common feedstock. The steam methane reforming of natural gas obtains syngas, containing large amounts of hydrogen together with CO₂, CO and methane. However, hydrogen can be produced without using fossil fuels by electrolysis. Instead of natural gas as feedstock, water is used. By applying a current to the water, the water molecules are converted to hydrogen and oxygen (James et al. 2016). This is a process that consumes large amounts of electricity, as noted above.

Creating new ways of reducing the iron ore is not the only way to decarbonise the primary steel production. Other options, such as carbon capture and storage (CCS), focus on capturing the exhaust gases from industrial processes and separate the CO₂ stream. The CO₂ is transported to be stored underground instead of releasing it to the atmosphere. The storage sites are commonly saline aquifers.
or old gas caves where the CO₂ is pumped down at high pressure. Other options discussed are ways to capture the CO₂ streams, but instead of storing the CO₂ find ways to utilise the gas. Steelanol is an example of carbon capture and utilization where the CO₂ is used as feedstock in fuel production (McKinsey 2018; International Energy Agency 2017). Both these abatement methods include changing the steel production process so that the CO₂ can easily be captured. These solutions are yet not proven in the steel industry and are also considered end of pipe solutions, meaning that the problem with fossil carbon emissions still remains. Therefore, CCS and CCU are not included in this study.

**Circular economy and demand side reductions**

To understand the concept of circular economy, or circularity, one must first understand the principles of the economy today. Historically, the modern economy has been what can be described as a linear economy into which raw materials and planetary resources are pumped to promote growth. In this linear economy, resources are consumed in a ‘take-make-dispose’ pattern. Companies extract materials, using them in the manufacturing of products, selling them to customers who later discard them when the products no longer serve its purposes. Even though the mind-set is slowly changing, this has been the norm, without concerns for externalities that may erupt. In addition, this behaviour is built on the false assumption that resources are endless, and the external input is needed to support economic growth (Accenture 2017; Ellen MacArthur Foundation 2015, 2012).

Little has been done to change this system until now. Instead focus has been on efficiency improvements along this straight line. A higher efficiency results in less materials and resources needed, which in turn leads to less externalities per produced unit. The concept of circular economy is a reaction to the linear approach. It comes from the understanding that our planet’s resources are not endless, and that growth and value can be created without the input of external virgin materials. Instead of discarding materials, energy and products at its end of life, the concept of circular economy aims to bend this straight line, reconnecting the end with the start, with the aim to form a closed loop (Accenture 2017; Ellen MacArthur Foundation 2015).

The essence of circular economy is thus to decouple value creation from the consumption of finite natural resources, and to replace the end-of-life concept in which products naturally end up as waste. With a change in product design, materials and systems, together with a change of the concept of ownership through new business models, waste can be limited and ultimately eliminated (Material Economics 2018). Perhaps the most important underlying principle to achieve this is the recycling of materials, by which materials are reused to make new products instead of being disposed through incineration or landfilled. But circular economy contains more than recycling. Achieving a circular system requires fundamental changes to fully support the recycling of materials, but also to maximise the value of the natural capital. This entails a set of new approaches: Materials recirculation, product materials efficiency and new business models that all contribute to a reduced demand for virgin materials, leading to less extraction of raw materials and production with lower CO₂ emissions as a result (Material Economics 2018).

By an increased *materials recirculation*, virgin materials can be replaced with recycled to a greater extent, leading to a lower demand of virgin materials production. Products that are no longer serving its original purpose are collected, reused and ultimately recycled. To increase the materials recirculation, it is necessary to create systems and incentives to collect scrap for recycling, and to a greater extent making sure as little as possible is lost as waste. With better sorting and limiting the in mixing of contaminants, the recycling process can be more economic with a higher quality of the output. New scrap can be limited by taking the production phase into consideration in product design, making sure that as much of the material as possible ends up in the final product. Lastly, the design of products can be done in ways that facilitate recycling and minimises the mixing of different materials (Material Economics 2018).
Through increased *materials efficiency* the same quality and service can be obtained with less material input. Large amounts of materials are lost in production today, but with new designs the amount of a material ending up in the final product can be increased, limiting the total material input. New advanced materials also have the potential to reduce the total material input required (Material Economics 2018).

With *new business models* the utilisation of products and materials can increase. By sharing services and products instead of owning one each, the overall utilisation of the products will rise, with less material input serving the same needs as a result. New business models also have the possibility to extend the lifetime of products when professionally managed. A higher utilisation can justify a higher initial cost, therefore promoting durability, maintenance and repairs. In turn circular business models also has the potential to facilitate better recycling, reuse and remanufacture (Material Economics 2018).

**Demand side measures in the steel sector**

The likelihood that the steel production will be decarbonised prior to 2050 is small, as it depends on the introduction of new technologies, currently not tried at commercial scale. Therefore, other measures are needed to gain time, and to achieve the necessary deep CO₂ cuts in the near future. Demand side measures through circularity principles have great potential to achieve this as it relies on a change in structure and behaviour, rather than new production technologies.

**Reducing steel losses**

Looking at the demand side, and how to make the most out of the steel that is already produced could play a crucial role in reaching established climate goals. By implementing circularity principles and circular business models, the amount of steel that is produced to meet demand can be cut drastically. Since the production volumes and CO₂ emissions go hand in hand, a demand reduction would imply a CO₂ reduction of the same proportion. The circularity principle can be implemented at the product level, leading to a decreased steel demand. Or it can be used to reduce losses in the steel cycle and making more scrap steel accessible for recycling (Material Economics 2018).

Throughout the material lifecycle, from production to recycling, large amounts of steel are lost or wasted. Taking care of these volumes holds a great potential to reduce the primary steel demand by boosting the recycling of steel and by reducing the total amount of steel that is needed to cover for what is lost. In the manufacturing of products for example, much of the steel that is used never makes it into products but is instead turned into production scrap (also known as new scrap) instantaneously at the forming or fabrication stage. As much as 18% of all steel is lost as new scrap in the manufacture of steel containing products, leading to an unnecessary high steel demand (Cullen, Allwood, and Bambach 2012).

Most of the steel is lost simply because it is never collected. Of all the new scrap only 79% is collected for recycling, a number that is almost identical to the overall scrap collecting rates at 78%. Some further 6% of all steel in never recovered as it belongs to an obsolete stock of inaccessible scrap, such as underground and submarine pipes, old constructions and buildings (Material Economics 2018). Lastly, when the steel scrap has been collected and is processed, some 5% of the steel is lost during the re-melting process. In this process alloys and trace elements are removed to ensure the purity and quality of the steel, hence the slagging losses could be reduced with better matching of input scrap and desired output (Price 2009).

**Steel demand reductions through Circular business models**

The second main demand side measure, is to find ways to reduce the amount of steel needed to provide a specific level of service, thus shifting focus from the production of steel to the use and design of the product itself. With new business models and product design that incorporates circularity principles, the way we use products and services can change drastically, with lower material needs as a
result (Ellen MacArthur Foundation 2015; Material Economics 2018). As mobility services and buildings account for more than 50% of all steel use, these value chains and products serve well for investigating the potential of circular methods in reducing the steel demand.

In Europe the automotive sector uses 12% of all steel, making it one of the most steel consuming sectors (The European Steel Association (EUROFER) 2018). A number that is likely to increase further as the number of cars per capita is steadily increasing (ACEA - European Automobile Manufacturers’ Association 2017). The use of the European car fleet is very inefficient with cars standing still 92% of the time, and an average trip having 1.5 passengers in a 5-seat car (Pasaoglu et al. 2012). The resulting overall the utilisation of only 2% leaves much room for improvement. The service that passenger cars provide is mobility, best measured in passenger kilometres (Material Economics 2018). By applying the circularity principles discussed in the previous section on a product, the service level can be sustained with less material input, by reducing the materials intensity of transportation through circular business models and increased materials efficiency.

Circular business models encouraging a shared car fleet, has the potential to tackle the low utilisation of cars. By sharing vehicles, the utilisation as well as occupancy per car increases. Therefore, fewer cars will be needed to provide the same level of mobility services, resulting in a reduced materials demand. In fleet-managed vehicles with higher utilisation also gives incentives for increased durability and better maintenance, as well as design and innovation, expanding the lifetime of vehicles and therefore the number of passenger kilometres served per material input. A shared car fleet would also affect the material efficiency (Material Economics 2018). To better adapt and to match different needs, the shared vehicle fleet would contain cars of different sizes, with a majority of smaller one or two-person vehicles, reducing the weight and material needs of an average car drastically. In a professionally managed vehicle fleet, reuse of parts and remanufacturing would be increased along with the share of the steel scrap being recycled. Modelling by Material Economics (2018) suggests that with professionally managed car fleets, based on circular business models, materials requirements could fall by as much as 75%. This entails that 63% of all cars are shared, 33% lighter vehicles, 15% remanufacturing, an occupancy of 1.93 per car and an increased lifetime by 94%.

Buildings account for one third of all steel use, and in similar way as in the automotive sector, circular leavers have the potential to reduce the steel demand in buildings (The European Steel Association (EUROFER) 2018). As with cars, increasing the lifetime of buildings is one of the most effective ways to reduce the demand for new steel, as it helps maintain the service of buildings with less material input. Even so, most buildings that are demolished is so because of changed architectural taste, new types of housing or commercial space is required or because renovating the building costs more than demolition, and not because it reached its technical lifetime (Hradil et al. 2014; Material Economics 2018). The lifetime of buildings could be prolonged not just by building with higher quality and better design, but also by making buildings more adaptable and modular. In this way the building can be changed more easily to cater for changed needs and requirements (Material Economics 2018).

There are several opportunities to further reduce the steel demand by addressing overuse of materials in the construction of buildings. Contractors are often not countable for construction waste, but instead bearing the cost of delays. This makes no incentives to reduce waste. On the contrary it results in extra materials being ordered as a buffer to avoid delays. In total 15% of materials are wasted during construction (Material Economics 2018). Over-specification of materials is common in the construction and design of buildings, by using more materials than technically needed for a safe construction. As much as half of all steel could be cut without compromising on design standards (Moynihan and Allwood 2014).

New materials and reuse of existing materials can also help to increase the materials efficiency. By changing to high-strength steel, 15-20% less steel is needed compared to conventional steel (Jernkontoret Research 2013). Today only 5% of all steel in buildings is reused, representing a small share of the total potential. With increased design, enabling reuse of steel this number could grow significantly (Steelconstruction.info 2018).
New business models and collaboration between actors can help to seize these opportunities with an increased material efficiency as result. Today, the construction industry is fragmented with different incentives along the value chain. By aligning incentives, vertical integration and a shift towards treating real estate as a service, long-term objectives are easier to achieve. This will help enabling design to promote materials efficiency, maintenance and buildings utilisation. Furthermore, new circular business models can also promote sharing of spaces, reducing floor area requirements (Material Economics 2018).

Scenario modelling done by Material Economics (2018) suggests that with materials efficiency strategies, steel use could be cut by 20-30% with less over-specification and use of high-strength steel and waste in construction could be cut by 5%. Circular business models could reduce floor area requirements by 5% through sharing. With more adaptable buildings and a design shift promoting durability, lifetimes of buildings could be increased by 40% on average. In total the steel reduction potential would be 50%.

**Difficulties in achieving increased recycling levels**

The advantages of the recycled steel production through the EAF route are large, especially regarding carbon emissions, feedstock and simplicity. With a saturating steel stock, there is a large potential to meet demand by recirculating end of life steel through secondary steel production, as demand will be driven mainly by a replacement of old structures and products. However, there are still obstacles hindering the share of recycled seeing its share grow substantially compared to today’s levels.

With today’s technology, recycled steel made from scrap with an EAF is not of high quality enough to meet all kinds of requirements. For some steel products there is a need of precise control over the purity of the input materials to obtain certain characteristic. This includes elements such as alloys, with copper being one of the most problematic. Knowing the input can be a challenge in secondary steel making, because the steel scrap is collected from many different sources, leading to a downgrading of the recycled steel (Barbara K. Reck and T. E. Graedel 2012). To handle the downgrading, most secondary steel is used in basic construction steel, such as rebar, that can tolerate less exact steel compositions and a higher share of contaminants. Another method that is practised to overcome the problematic of downgrading, is to dilute the secondary steel with uncontaminated primary steel to reach an acceptable level (Material Economics 2018).

If recycled steel is to take a larger share of the total steel production, measures need to be taken to limit copper contamination and downgrading of steel. Such measures involve using technologies to better sort steel scrap by type of alloy, making it possible to match the input content with the desired output of the secondary steel. Furthermore, the separation of end of life products needs to improve to avoid mixing clean steel with contaminated steel or copper scrap. By doing so, scrap of different qualities can be used for different purposes (Haupt et al. 2017). Much can also be improved by a change in product design and an improved dismantling of products to make it easier to separate parts without mixing steel scrap of different qualities and achieve better sorting of scrap material (Material Economics 2018). The availability of steel scrap for secondary production is also a limiting factor. A higher production share of recycled steel will require that more steel scrap be collected to be re-melted in the secondary steel production, a topic discussed below.
Results

Emissions for all technology routes decrease

The electricity needs to produce one tonne steel varies greatly between the three technologies studied. Therefore, a future shift to a completely decarbonised power production affects the associated CO₂ emissions differently in the three production routes (figure 2). With carbon free electricity the secondary EAF production becomes almost completely decarbonised, with emissions reduced from 0.33 to 0.01 tonne CO₂ per tonne steel, assuming that small emissions from the electrodes are unavoidable. A smaller reduction is seen in the BF-BOF production, with emissions per tonne steel only decreasing slightly, from 1.92 tonnes today to 1.61 tonnes CO₂ 2050, including efficiency improvements of 7.11% by 2050 (which is the same efficiency improvement rate as has been seen since 1990). However, this is not enough to achieve the deep emission cuts necessary.

Instead, the necessary emissions cuts in primary steel production will need to come from the introduction and up scaling of hydrogen-DR steel production. By completely switching to renewable electricity the carbon emission from hydrogen-DR would decrease drastically from 1.09 to 0.01 tonnes CO₂ per steel produced, with the remaining emissions coming from the electrodes in the EAF as discussed above. Since the hydrogen-DR requires large amounts of electricity, mainly through the electrolysis to produce hydrogen, the need for renewable energy will increase, which is discussed below.

![Emission factors for each production route](image)

Figure 2 showing emission factors for the studied technology routes. The electricity production is assumed to be decarbonised in 2050.

Business as usual and Hydrogen-DR

If the development continues as of today without major interference, innovations or implementations of circular methods or business models, the European steel demand in 2050 is projected to increase by 16% from 166 Mt to 193 Mt annually. The production split between secondary and primary production is estimated to be the same as today with 61% being primary production and the resulting 39% being secondary production. The efficiency of BF-BOF primary production will improve by 7.11% linearly, until 2050. In the same way, renewable electricity is assumed to reach 100% by 2050. The result is therefore an emission factor of 1.61 tonnes CO₂ per tonne primary steel in 2050. For secondary production the emission factor will be 0.01. The consequence of a business as usual scenario will be that steel industry itself causes annual CO₂ emissions of 188 Mt (figure 3). This is a small decrease with 13% lower emissions than today. The cumulative CO₂ emissions by 2050 will reach 7.1 Gt.
With the introduction of hydrogen-DR as a supply side measure, annual and cumulative carbon emissions will decrease. The technology is assumed to be ready for small-scale commercial production by 2030, and to increase its production to 30% of the total steel production in 2050, taking its share from the primary BF-BOF production. The share of hydrogen-DR production is set to be 1% in 2030, 4% in 2035, 10% in 2040, and 20% in 2045 ultimately reaching 30% in 2050. The shift of technology towards hydrogen-DR could cut annual emissions by about half in 2050, from 188 Mt to 96 Mt (figure 4). However, the delay that comes with up scaling of the technology results in a smaller effect on cumulative emissions, which decrease by 12% to 6.4 Gt CO₂.

### Mitigation through demand side reductions

Future steel demand does not have to increase as much as predicted. The demand side measures are modelled by changing the losses and circular principles in the demand model. Obsolete stock is halved to 3%. Collected scrap increased to 92%. New scrap generation reduced by a third to 12%. Collection of new scrap increased to be 95%, an increase of 20%. Re-melting losses are reduced to be 3% (a reduction of 40%). To model the effects of new business models, the demand reductions in the value chains studied has been altered. In transportation, 50% of the potential has been used, resulting in reductions of 33.5%. In buildings, 40% of the potential is used, resulting a reduction of 20%.
With these measures, the annual steel demand could be reduced by as much as 27% in 2050, from a business as usual scenario of 193 Mt, to a circular scenario with an annual steel production of 141 Mt (figure 5). The reductions from circularity principles are 6% (12 Mt). The reductions from a lower demand as a result of circular business models are 21% (40 Mt).

![Annual steel demand](image)

**Figure 5 showing annual steel demand in the business as usual scenario and with circularity leavers applied.**

Even with a maintained technology mix and the same emission factors as of the business as usual scenario, the demand reduction alone would result in a cut of CO₂ emissions by almost a third (27%), 51 Mt, from annual levels of 188 Mt to 137 Mt in 2050 (figure 6). Cumulative emissions until 2050 would decrease from 7.1 Gt to 5.9, a drop of 17%.

![Annual CO₂ emissions with circular demand reductions](image)

**Figure 6 showing annual CO₂ emissions with circular demand reductions. The technology mix is same as in the business as usual scenario.**

As recycling is at the core of circular economy, a complete utilisation of circular abatement methods includes a major change in the production mix towards secondary steel production. A linear increase of EAF production from today’s 39% to 70% has large effect on CO₂ emissions. Combined with the introduction of hydrogen-DR in 2030, producing the last 30% of all steel in 2050, annual emissions...
are almost eliminated entirely, decreasing to 0.7 Mt CO₂ in 2050 (figure 7). In this scenario the cumulative emissions are 4.4 Gt, almost 40% lower than the business as usual scenario.

**Figure 7 showing annual CO₂ emissions with circular demand reductions and the implementation of hydrogen-DR.**

### The production mix will change drastically

The production shares will practically turn upside down in the coming 30 years in the circular scenario. During the period, primary BF-BOF production will be completely phased out by 2050 and replaced by hydrogen-DR as the production route for the remaining virgin steel. The introduction of hydrogen-DR takes place in 2030, with its first small commercial plant. The production volumes will thereafter increase substantially until 2050. The share of recycled steel will increase linearly with the result that a majority of the steel will be produced through the EAF route (figure 8).

**Figure 8 showing annual production volumes in the circular scenario.**
Electricity and hydrogen demand will increase

With the replacement of BF-BOF production by hydrogen-DR, combined with a higher share of secondary EAF production, the electricity consumption will rise substantially due to the electricity intensity of these technologies and the electricity need for hydrogen production. Compared to the business as usual scenario the annual electricity consumption will increase by 260% in 2050, with the electricity need reaching 194 TWh annually, compared to a business as usual level of 54 TWh. Compared to today’s levels the increase is even larger, with 2050’s needs being 321% higher (figure 9). The production of hydrogen will account for more than half of all electricity with a demand of 101 TWh in 2050.

![Figure 9 showing annual electricity need for the business as usual and circular scenario.](image)

As hydrogen-DR is introduced, the need for hydrogen as a feedstock in steel production will increase the European hydrogen demand substantially. In the circularity scenario, with hydrogen-DR reaching 30% of the total steel production in 2050, the hydrogen needed to support the process reaches 2.2 Mt annually (figure 10). This production level is 30% higher than today’s European hydrogen production of 7 Mt.

![Figure 10 showing annual hydrogen demand for hydrogen-DR production in the circular scenario.](image)
Discussion

In the climate debate, many put their hope to new technical innovations, claiming that industry and companies will find ways to lead us out of the climate crisis. There are technical solutions that can play a large role in the transformation of the European steel industry, but they will unlikely make it all the way alone. As the demand for steel grows in a business as usual scenario with almost 20%, so does the CO₂ emissions. The introduction of low-CO₂ processes in steel production has the theoretical potential to reduce these emissions drastically. With hydrogen-DR taking a 30% share of the primary production together with efficiency improvements in the BF-BOF route, up to 50% of the annual emissions can be reduced by 2050 compared to a business as usual scenario. It may sound like a great achievement but is still only halfway of reaching the set target of net zero.

Looking at cumulative figures the scenario plays out even worse, as in a climate change context the cumulative emissions are the crucial part of reaching the below 2 degrees goal. The technology shift does not help much in limiting these cumulative emissions, with the remaining 6.4 Gt still being a tenth of the total CO₂ budget until 2050, globally. Considered that we are looking at one of several major industries and one single continent, 10% of the global budget is an enormous number. This said, the technology shift is needed, but alone without other means of mitigation the effects in the implementation of new processes are not deep enough and comes too late.

Even with a successful development and introduction of hydrogen-DR, it is unlikely that a production route that is introduced on the market in the 30’s would be able to ramp up its production to produce more than 30% of the total steel demand in just two decades. If no circularity is applied and all primary production is to be produced through the hydrogen-DR route the volumes would reach over 100 Mt annually, almost double the amount of steel produced through the EAF route today.

What these results show is that the change needs to happen now if the cumulative emissions are to decrease significantly compared to today’s pace. It also shows that if the BF-BOF production is to be phased out before 2050, the total production volumes need to be cut for this to be a realistic scenario. Circular principles have the potential to widen the solution set by introducing means by which the demand side can be altered to be part of the solution. As demand side measures have direct impact on emission levels, the effect can be more swift than the introduction of new technologies, as changes in business models and usage theoretically can change overnight, compared to the development of new steel production routes. This helps save time when the technologies needed are not yet in place.

Overall the result tells us that there are three aspects that together become the solution, but neither of them reaches all the way by itself. The demand reductions are needed to create an immediate effect and to help saving time by reducing the emissions from the unavoidable BF-BOF production in the near future. It will also contribute by minimising the gap that needs to be filled by EAF and hydrogen-DR, by making the steel production volumes smaller. Similarly, the increased recycling of steel will reduce the need of primary production by taking larger shares of the total steel production. Lastly, as there will still be a need for primary steel, due to the limits of recycled steel and scrap availability, new technologies such as hydrogen-DR are needed to provide climate neutral virgin steel.

The production shares of the different process routes and the implementation of circular principles are naturally very theoretical. The point of this study is not to show how the future is most likely to be, but rather showing that a combination of new technologies and circularity has the potential to move the European steel industry towards zero emissions. Some of the measures used in the modelling in this study might turn out to be harder than expected, and play a smaller role, whilst others might happen faster and to be implemented at a higher rate. To take this into consideration only a part of the total potential of the circular demand reductions has been used.
The necessary technological shift comes with great challenges

There are many pieces that need to fall in place for such a scenario to play out successfully. The technology scenario can be seen as quite optimistic, assuming that processes that have never been proven at commercial scale will be producing 30% of all European steel in just 30 years. Putting so much hope to the development of one type of technology, when so much is at stake, would be risky. It is likely that the introduction of a new steel making process will take time. However, with the right incentives and policies, the development and introduction might happen quickly and as four of the world’s biggest steel companies are all putting hope to the one and same process, hydrogen-DR, the prospects seem to be in favour. Furthermore, this study focuses solely on one technology, and there are other that might evolve to be the dominant challenger, but it might not be likely that it will happen sooner than in the modelled scenario. Even with a successful development of hydrogen-DR there is a risk that companies producing primary steel through the BF-BOF route would prefer to delay the introduction of hydrogen-DR since its current assets have not yet reached its technical lifetime. Shutting down an existing plant years before the calculated end date could be way too costly to be economically motivated, therefore delaying the shift from BF-BOF production towards a climate neutral hydrogen-DR production to avoid these stranded assets.

Apart from the new hydrogen-DR technology itself, the scenario puts high demands on the availability of hydrogen and carbon free electricity. Increasing the production of hydrogen is probably possible since the technology to produce hydrogen with electricity via electrolysis is already in use and the only feedstock needed is salt and air, both abundant resources. The challenge is likely to be in supplying the large amount of renewable electricity that will be required in the future. As it is not only the steel industry that will need more electricity but presumably also most industries will move from fossil-based feedstocks and fuels towards an electrification of processes. This together with the electrification of transportation and a general electrification of the society as a whole would make the demand for renewable electricity skyrocket. However, as mentioned before, the assumption that the power production will be completely fossil-free in 2050 is a necessary if the industry and the society as a whole will have a chance of reaching the Paris agreement.

The steel industry might be blessed by the coming reliance on hydrogen if renewable electricity would be scarce and expensive. The hydrogen needed in the steelmaking could be stored on site for short periods and therefore the possibility exists to produce the hydrogen during periods of higher renewable electricity availability with lower prices. This could be during nights when less industry is active and when the weather conditions promotes either solar or wind power. As half of the electricity need comes from the production of hydrogen this would make the industry less sensitive to electricity cost peaks.

Enabling a circular economy and the needed transformation

Achieving the demand side measures modelled in this study requires big changes, in which new business models are key. Not only because of the increased sharing potential it provides but also due to the change in value chains and the control it gives over material flows. Therefore, it is possible that the transformation towards circular business models itself can promote and create incentives for a change in product designs, increased recycling and lower materials demand.

One example is the challenges that need to be tackled to successfully reach the needed levels of recycled steel. Copper contamination and the output quality of the recycled steel have no clear solutions. The new technologies that are being developed might help, but as long as there is no ways to remove the contaminants or completely separate lower quality scrap from a mixed pool, other ways of overcoming the problem are needed. The value chain control that new circular business models can promote could be a solution or at least a move in the right direction. Once material flows are controlled it is easier to make sure that different materials are not mixed prior to recycling and it would give incentives to produce products that are easy to dismantle and recycle.
It might sound like a big achievement that recycled steel would account for 70% of the total steel production in 2050. But in absolute number the change is not that drastic, thanks to a decreased total steel demand. In absolute numbers the steel production through the EAF-route would only increase by 50% from today’s annual production of 65 Mt to 98 Mt in 2050. With new business models this is likely a feasible increase.

Once new circular business models that promote a sharing economy are the norm many pieces are likely to fall in place with it. Less material would be used for the same amount of service with increased sharing and utilisation. Lifetimes would be longer as it lies in the interest of the business, and scrap would be handled with more care. Which such business models the development would be a reinforcing loop promoting progress within all these aspects.

The change has already started, with more companies built on circular business models being added to the list every month. The question is what it will take to push this transition all the way, to have the full effect that is needed in the scenario. Without the right policies the shift might not happen quick enough. Recycling of steel needs to be promoted with new regulations and incentives making it more valuable to keep control over the end of life steel and encouraging costumers to recycle their products. One type of measure could be to put regulations and taxes in place that will push the raw material prices, therefore making recycled steel cheaper in comparison. This in turn would promote better sorting of steel scrap, higher collection rates and improved design to reduce losses in production. Existing regulations that affect circular business models need to be revised to better promote sharing. To gain public support it could be effective to introduce labelling that show the positive effects of a shared service or a product designed to promote circularity.

**Understanding the economics is crucial**

This report has modelled the steel industry from a technological perspective, and no analysis on the economics of this transformation has been made. Therefore, this study only shows what could be feasible from a technological point of view, not taking what is economically realistic into account. As the development of new technologies is costly, the risks for individual companies developing and implementing new processes are likely to be large.

Apart from the actual development of new technology routes, the shift itself could turn out to be an economic risk. As in every industry, the business needs to be as streamlined and efficient as possible, realising high load factors in the steel making process. The change of processes and technologies discussed in this study might come with disruptions, such as due to the replacement of industrial parts and equipment. It is likely that this major transformation therefore would imply production stops, which could be very costly, especially for an industry already under pressure. It could also be that the introduction or expansion of hydrogen-DR, EAF or other processes would imply that several processes will have to run in parallel, doubling the operational costs for the manufacturer, while the sales in produced steel remains the same.

With big investments, such as steel plants, costs are carefully calculated to ensure the right level of profitability. In these calculations the lifetime and the productions capacity are of high importance. Since the lifetimes of steel plants are in the length of decades, it can take long time before the investments have reached its payback time. Therefore, closing a BF-BOF plant before its technical lifetime is reached would most likely come with great costs. This study has not taken into account the age of existing BF-BOF plants and its estimated time until the technical lifetime is reached. As it is unlikely that companies would replace a BF-BOF plant several years prior to the original plans this analysis would provide valuable input to estimate a realistic replacement rate of the BF-BOF plants.

Steel is a commodity that is traded globally with many actors based outside of the EU, and as mentioned the European steel industry has still not recovered fully after the financial crisis. If the European steel industry would take the lead in the technological transformation it would be likely that European steel prices would increase due to the large investments. On a tough global market this could
hit the European industry hard, and domestic production could be replaced by international import. Therefore, it is of highest importance for governments and the EU to support the steel companies in ways that reduce this risk and encourage the European steel industry to take the lead. In the end this could turn out to be a good move, when demand for zero carbon steel rises together with higher climate ambitions globally.

A lower demand will have direct effects on the European steel industry. The implications of a lower demand are dependent on global trends and competition and are affected by how the export market develops. On the positive side, a lower steel demand as a result of circular measures will help cutting the overall costs for the industrial transformation. With lower production volumes, less new production capacity is needed, resulting in lower investment costs.

If the European union is to reach its climate goals, the transformation of the industries that are considered hard to abate must to accelerate. When the solutions are presented, it is up to policymakers and politicians to decide how to push the change in the most efficient way. Regulations and incentives are needed, but they can take many different forms. Much research is done in finding technical solutions, eliminating the CO₂ emissions, but finding ways how to put these in place is as important. In the end what needs to be done is to create an environment in which emitting CO₂ is more expensive than being part of this industrial transformation.

**Further studies**

The scope of this study has been the main steel making process, excluding the preparation of iron ore and coke and limiting the modelling of downstream processing. To get the greater picture, from extracting raw materials to a finished product the scope would need to be widened. Downstream processing of crude steel is not investigated in detail in this study as it is both complicated to analyse and not part of the main process. Looking deeper into downstream processing and the extraction of raw materials could therefore be a natural step in further research. However, it is believed that the greater share of emissions from one tonne steel produced is covered in this study.

It is possible to discuss whether the circular principles and demand side measures are set to a realistic level in the modelling. What levels are reasonable to believe are feasible to achieve until 2050? This question is impossible to answer and would need much more investigation to come closer to the true answer. The same applies for the introduction and scale up of new technologies. Are the shares in steel production realistic, and is the implementation rate of hydrogen-DR too quick? As already mentioned this study does not try to answer this questions but instead show that a scenario containing circular measures combined with new technologies has the potential to make the deep emission cuts necessary until 2050.

During the transition from today’s industry to 2050 much can happen. It is likely that transitional technologies and processes will be used during this transition, before the development of hydrogen-DR or other technologies are finalised or the economics and policies promoting such technologies are mature and in place. Such technologies could help reduce emissions along the way, resulting in decreased cumulative emissions in 2050. CCS could play an important role in the transition to be able to cut emissions within the next ten years.

Another interesting aspect not discussed in depth in this study are other positive effects that the transformation of the European steel industry can bring, creating additional value to the society and the European economy. Effects from the technology shift could be increased air quality when less coke is burnt in steel plants and less pollution from the extraction of raw materials. Going from buying products to buying services is a shift that is likely to affect us on a psychological level and could we worth investigating further.
Conclusion

The task to create a climate neutral European steel industry is not an easy one, with no universal solutions or quick fixes at hand. Putting all hope to technical solutions is too optimistic, as it would require extraordinary speed in development and implementation of processes, not yet proven at scale. The climate goals are set for 2050, but as cumulative emissions are as important to minimise climate change, actions are needed now since time is crucial. Putting all hope to one or a few technological solutions is risky when so much is at stake. However, new technologies such as hydrogen-DR, will need to be part of the solution when transforming the steel industry to become fossil free. Considering risks and time, the solution set needs to widen if a zero-emission steel industry is to become a reality in 2050. It needs to comprise both supply and demand side reductions. Combining these types of measures makes to most out of the potential and maximises the CO₂ reductions by enabling a shift of technology routes for the productions of steel.

Circular measures directly affect steel demand, with fewer emissions as result. The demand reduction alone has the potential to reduce emissions from steel production by one third in 2050 and nearly 20% of the cumulative emissions. It also enables the increased recycling of steel, shifting production from the emission intensive BF-BOF route to the low CO₂ EAF process. A lower steel demand also lowers the threshold for hydrogen-DR to provide all the needed primary steel when the total volumes are lower.

To reach near zero emissions in 2050 a combination of demand side and supply side reductions is needed. On the supply side, the shift from BF-BOF to hydrogen-DR primary steel production results in the biggest cuts. But efficiency improvements and a decarbonisation of the electricity production are also essential. In this study the demand side measures take expression as lower demand and a higher share of recycled secondary steel production. It also enables the phase out of BF-BOF as a steel production route by 2050. The combination of these measures together has the potential to reduce the cumulative emissions by 40%.

This study shows that it possible to reach zero emissions with a combination of circular measures and new technologies. It has not investigated what is required for this transformation to take place. The investments needed are large, especially for individual companies, which need to take big risks. Regulations and incentives will be needed to support the companies, helping them to reduce the risks. Policies are also needed to support new circular business models and promote increased steel collection rates.
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