PROJECTING THE EU’S END USE SECTOR STEEL DEMAND TILL 2050 TO INVESTIGATE THE SHARE OF HIGH & LOW STEEL GRADES AND BOLSTER DECISION MAKING IN PRODUCTION PATHWAYS

Master Thesis

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Abstract

Steel production in the EU emits a large share of the regions greenhouse gases. The intensity of these emissions depends on the production route, with the Blast furnace- basic oxygen furnace emitting between 1.6 to 1.9 tCO_2/t crude steel and the electric arc furnace emitting between 0.6 to 0.9 tCO_2/t crude steel. Choices made on the production pathway depend on the grades of steel in demand since certain grades cannot be met with 100% scrap feed. Therefore, it is imperative to project the steel demand in the EU based on end use sector activity as different sectors have different steel grade requirements. The share of high and low grade steel in the EU in 2050 is 53% and 47% respectively with transport, machinery and tubes contributing to 60% of the high-grade demand while construction contributing to 69% of the low-grade steel demand. With a 53-47% mix of high and low grade steel demand, the integrated route using a blast furnace- basic oxygen furnace for high grade steel production and an electric arc furnace for low grade steel production is proposed. Using oxyfuelling in the blast furnace with CCS or smelting reduction with CCS would reduce the CO2 emissions from the integrated route by 55% by 2050.

Acknowledgements

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Abbreviations

BF – Blast Furnace

BOF- Basic Oxygen Furnace

EAF- Electric Arc Furnace

LDV, HDV – Light Duty Vehicles, Heavy Duty Vehicles

HEV – Hybrid Electric Vehicle

PHEV – Plug In Hybrid Electric Vehicle

EV- Electric Vehicle

FCEV – Fuel Cell Electric Vehicle

CCS – Carbon Capture and Storage

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Introduction

Steel is an alloy of iron and other elements, primarily carbon and has a high tensile strength and low cost. Due to these properties, it is used in a wide variety of products such as buildings, vehicles, packaging and everyday appliances. Figure 1 shows the end use sector share of steel demand in the EU.

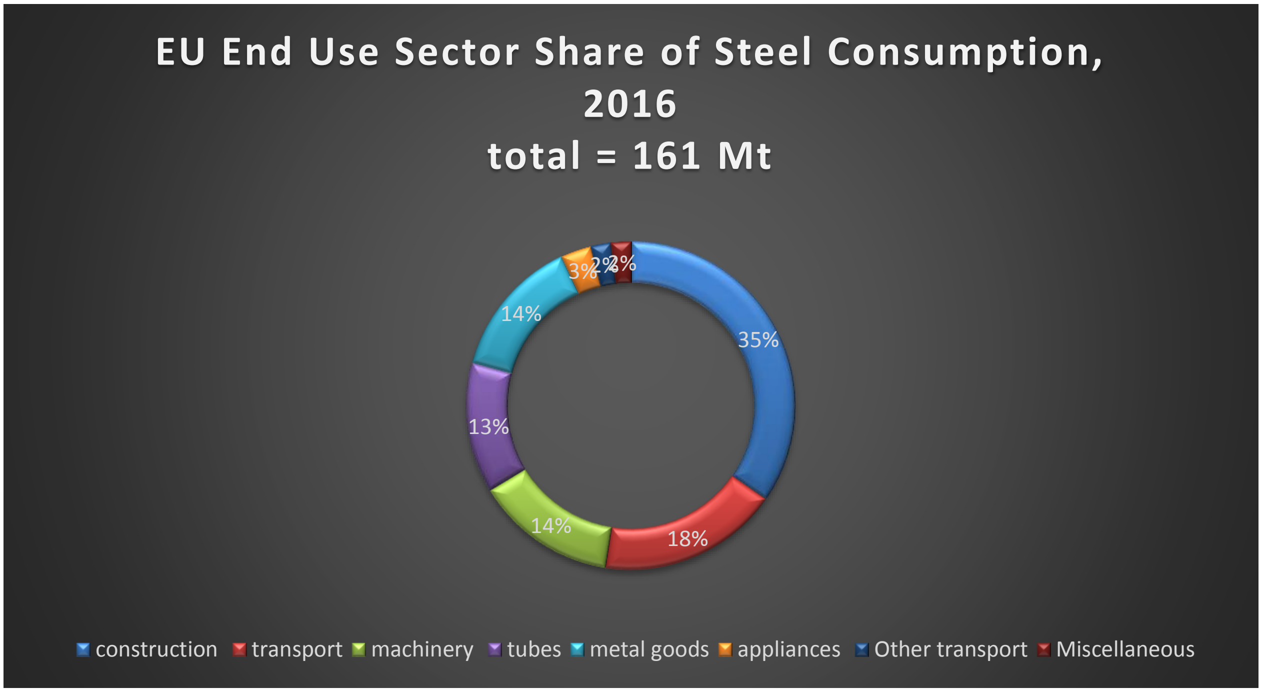


Figure 1: EU steel consumption by sector, 2016

Source: EUROFER, Economic and steel market outlook, 2016

Steel production accounts for ca. 25% of industrial and 9% of anthropogenic energy and process-related greenhouse gas emissions (Pauliuk et al, 2013). With an ever-growing population, demand for products that use steel will increase thereby increasing steel demand. Population increase and rapid growth of developing countries like India and China will further intensify steel demand and greenhouse gas emissions in the future.

Therefore, in order for EU steel industries to plan for future sustainable scenarios for the EU, long term (2050) steel demand projections within the EU need to be investigated.

Conceptual Framework

Currently most demand projection models involve a combination of population growth and GDP growth (Neelis & Patel, 2006). These models mainly analyze the Intensity of Use (IU$), which can be described as the material consumption per unit of GDP (Neelis & Patel, 2006). When plotting the IU$ for steel demand based on GDP/capita, it shows an inverse u shape curve (Figure 2).

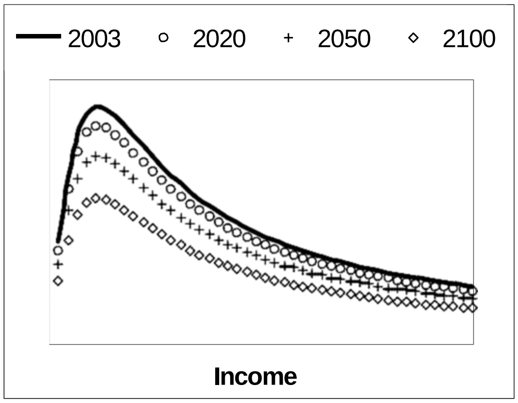


Figure 2 The intensity of steel use and a function of GDP per capita

Source:(Neelis &Patel, 2006)

As a country develops and its GDP grows, a shift to less material-intensive products is witnessed. Materials are used more efficiently and a shift from lower quality materials to new higher quality ones is seen (Neelis & Patel, 2006). This implies a decoupling between material use and GDP at high GDP levels. When using the IU$ method, the focus is only on material flow and the in-use stock is neglected.

Steel –containing products provide service over several decades and hence, the in-use stock of steel rather that the consumption flow is a more adequate service measure (Pauliuk et al, 2013). By extrapolating steel consumption trends, one ignores the dynamics of the in-use stocks and one can therefore neither connect consumption to the actual service provided, nor estimate the future supply of post-consumer scrap from products leaving the stock at the end of their lifetime. Instead, availability of postconsumer scrap is often taken for granted (Pauliuk et al, 2013).

Therefore, in order for EU steel industries to plan for the future, it is important to investigate steel demand projections for the long-term based on sector developments as it includes in-use stock and these sectors use different grades of steel with a required scrap % which require different modes of production (primary, secondary and scrap recycling) (Worrell, 2016). Knowing the demand projections of end use sectors, the share of different grades of steel and its scrap requirements will aid steel makers in their decision-making process of investing in a new blast furnace- basic oxygen furnace (BF - BOF) or Electric Arc Furnace (EAF). This will in turn help assess the CO2 emissions of the desired production route.

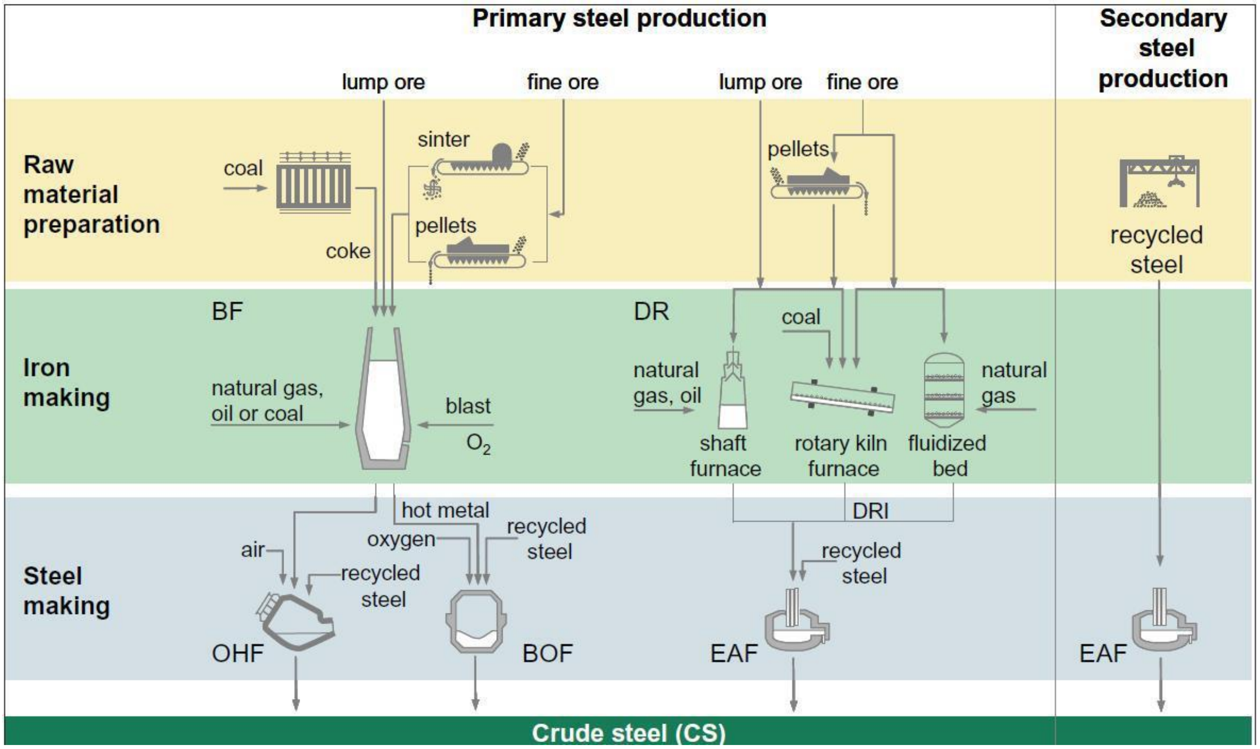


Figure 3: 3 steel making process (World Steel Association, 2008)

Figure 3 shows the three main production methods for steel. Primary production encompasses the first two methods (blast furnace and direct reduction) and secondary production uses scrap/recycled steel.

The first method shown is primary steel making when using a blast furnace (BF). Coke (a coal product), and iron ore (in the form of sinter or pellets) are added to a BF. The burning of coke in combination with hot blasts of air in the furnace, heat up the iron to 1530° C. Steel becomes liquid at this temperature. This allows chemical reactions to take place and remove impurities (Worrell, Blinde, & Neelis, 2010). The molten iron is then transferred to a basic oxygen furnace (BOF) where pure oxygen is added to reduce the carbon content of the iron to create steel. The steel is then rolled, flat or cast into a slab.

The second method is the production of direct reduced iron (DRI) through the process of direct reduction (DR). This process eliminates the need for coke plants, sinter plants, blast furnaces and basic oxygen furnaces to save energy. Instead, lump ore or pellets are gasified with natural gas to form a melt and to remove the impurities. This is followed by the use of an electric arc furnace (EAF) to make steel out of the metal by using an electric current.

The third method is the secondary steel production method which uses 100% scrap/recycled steel directly in an electric arc furnace (EAF) and uses electricity instead of coal and coke to form liquid metal so it can be cast and re-used.

Research Question

Based on the information provided in the conceptual framework chapter, the following research question is formulated:

> *What is the EU's projected end use sector annual steel demand and share of steel grades till 2050, and which production routes are preferred to meet those grades and what are the associated emissions and* CO_2 *abatement recommendations for that production route?*

In order to answer this research question the following sub-questions have been formulated:

1. **What are the main end use sectors for steel and what are the key drivers within these sectors that effect steel demand?**
   Most studies use population growth and GDP to determine steel demand. But as mentioned in the conceptual framework chapter this method is not a good representation of projecting steel demand since steel products have a long lifetime (depending on its use). Therefore, investigating the end use sectors rather than an individual product is a better approach since it provides the share of different grades of steel.

2. **What are the identified steel grades that will have a major share in future steel demand?**
   Investigating the different sectors aids in identifying the different types of steel (steel grades) used in these sectors. Production methods depend on the grade of the steel and therefore aid in investment decision making in relation to production process. This sub question will help assess the share of high and low grade steel demand and if scrap supply can meet demand.

3. **What current technologies are used in the production of the identified steel grades and their associated carbon emissions?**
   Once the share of steel grades is identified, an investigation on the current technologies used to produce the desired steel grade needs to be investigated. This will provide information on the current energy usage and carbon emissions.
   This will further help provide recommendations on ways to reduce carbon emissions by 2050

Methodology

During the commencement of this research, it was agreed with Tata Steel that five key sectors will be investigated for steel demand. These sectors are: - Construction, transportation, energy technologies (Wind, PV), machinery, tubes and appliances (EUROFER, 2016).

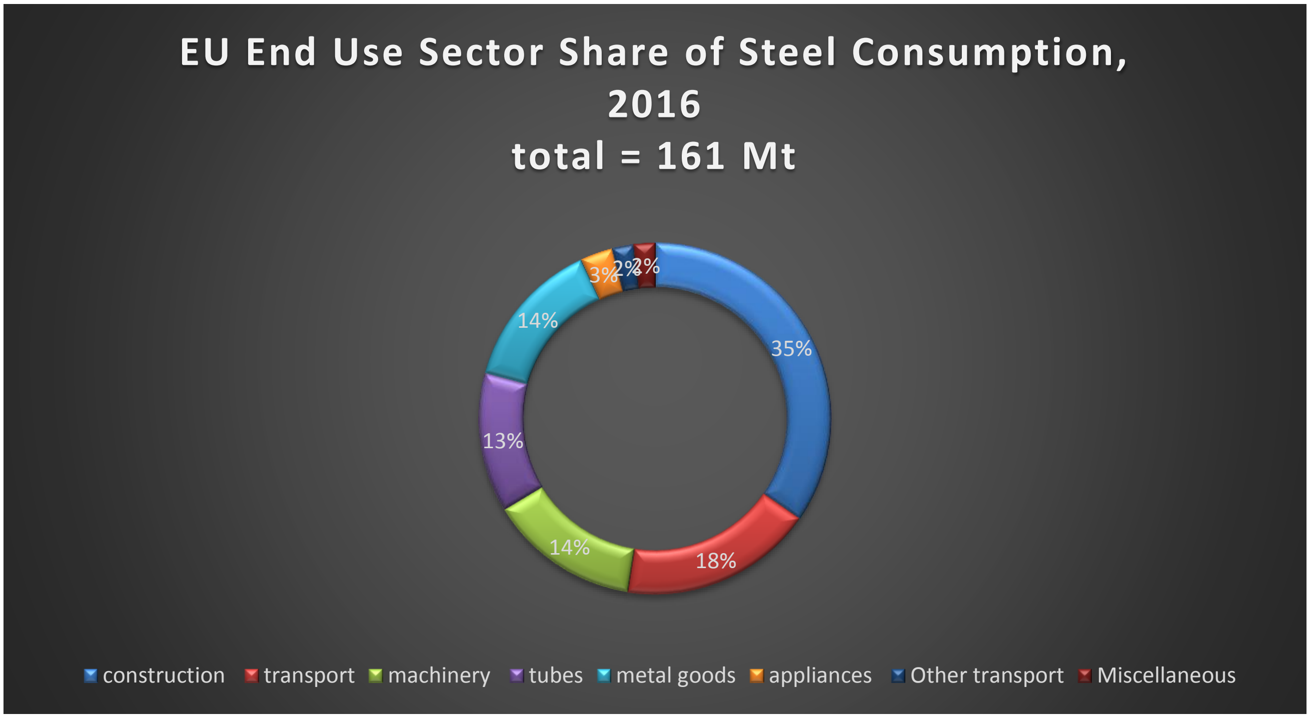


Figure 4: 2016, EU end use sector steel demand

Source: EUROFER, Economic and steel market outlook, 2016

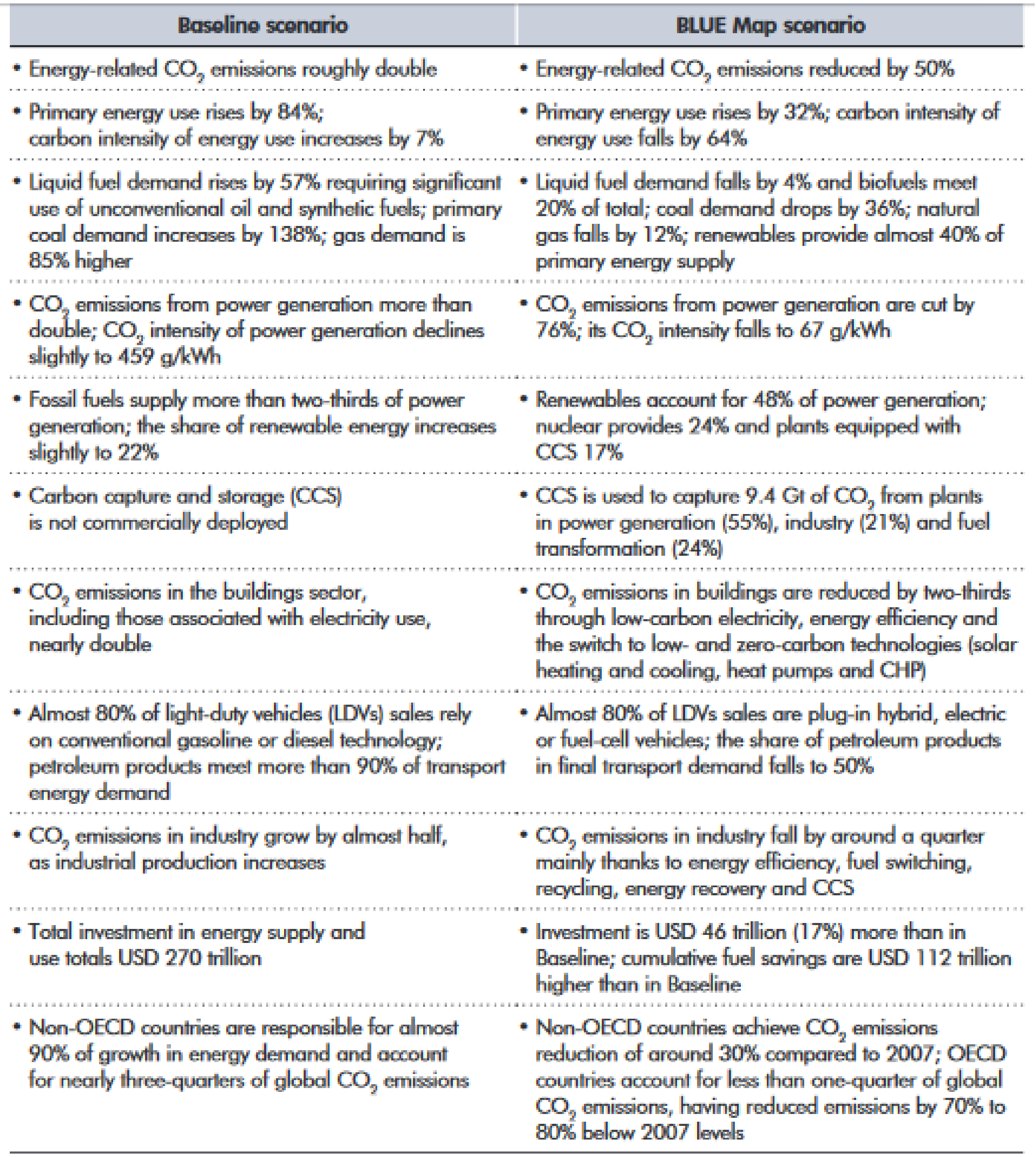
Existing literature, scenario tools and studies will be used to investigate the future steel demand for these sectors and the key drivers of this demand.

To investigate the projected steel demand for these end use sectors, future scenarios till 2050 need to be identified since activity in these sectors will depend upon future scenarios.

Scenarios defined in the *Energy Technology Perspectives 2008* (ETP 2008) *(*IEA, 2008a) will be used in this research. These scenarios were then updated to the year 2050 in the report *Energy Technology Transition for Industry (*IEA, 2009).

The BLUE scenarios (ETP, 2008) examine the implications of a policy objective to halve global energy-related CO_2 emissions in 2050 compared with today’s level. The outcomes implicit in the BLUE scenarios are consistent with a global rise in temperatures of 2°C to 3°C, but only if the reduction in energy-related CO_2 emissions is combined with deep cuts in other greenhouse gas (GHG) emissions. The BLUE scenarios are coherent with the 450 parts per million (ppm) scenario of the WEO 2008. The 2010 BLUE Map scenario was also used as an updated version of the 2008 scenario.

The detailed energy and emission trends under the baseline and BLUE Map scenario investigated by the IEA are provided in figure (5)



Baseline scenario	BLUE Map scenario
• Energy-related CO_2 emissions roughly double	• Energy-related CO_2 emissions reduced by 50%
• Primary energy use rises by 84%; carbon intensity of energy use increases by 7%	• Primary energy use rises by 32%; carbon intensity of energy use falls by 64%
• Liquid fuel demand rises by 57% requiring significant use of unconventional oil and synthetic fuels; primary coal demand increases by 138%; gas demand is 85% higher	• Liquid fuel demand falls by 4% and biofuels meet 20% of total; coal demand drops by 36%; natural gas falls by 12%; renewables provide almost 40% of primary energy supply
• CO_2 emissions from power generation more than double; CO_2 intensity of power generation declines slightly to 459 g/kWh	• CO_2 emissions from power generation are cut by 76%; its CO_2 intensity falls to 67 g/kWh
• Fossil fuels supply more than two-thirds of power generation; the share of renewable energy increases slightly to 22%	• Renewables account for 48% of power generation; nuclear provides 24% and plants equipped with CCS 17%
• Carbon capture and storage (CCS) is not commercially deployed	• CCS is used to capture 9.4 Gt of CO_2 from plants in power generation (55%), industry (21%) and fuel transformation (24%)
• CO_2 emissions in the buildings sector, including those associated with electricity use, nearly double	• CO_2 emissions in buildings are reduced by two-thirds through low-carbon electricity, energy efficiency and the switch to low- and zero-carbon technologies (solar heating and cooling, heat pumps and CHP)
• Almost 80% of light-duty vehicles (LDVs) sales rely on conventional gasoline or diesel technology; petroleum products meet more than 90% of transport energy demand	• Almost 80% of LDVs sales are plug-in hybrid, electric or fuel-cell vehicles; the share of petroleum products in final transport demand falls to 50%
• CO_2 emissions in industry grow by almost half, as industrial production increases	• CO_2 emissions in industry fall by around a quarter mainly thanks to energy efficiency, fuel switching, recycling, energy recovery and CCS
• Total investment in energy supply and use totals USD 270 trillion	• Investment is USD 46 trillion (17%) more than in Baseline; cumulative fuel savings are USD 112 trillion higher than in Baseline
• Non-OECD countries are responsible for almost 90% of growth in energy demand and account for nearly three-quarters of global CO_2 emissions	• Non-OECD countries achieve CO_2 emissions reduction of around 30% compared to 2007; OECD countries account for less than one-quarter of global CO_2 emissions, having reduced emissions by 70% to 80% below 2007 levels

Figure 5: Emission trends of the BLUE Map scenario

Source (IEA, 2010)

For the transport sector, the SULTAN (Sustainable Transport) illustrative scenario tool developed by CE Delft and TNO for the European Commission's DG Climate Action project *EU Transport GHG: Routes to 2050 II*, will be used. This tool has been developed as a high-level calculator to help provide indicative estimates of the possible impacts of policy on transport in the EU. For the SULTAN scenario tool a central Core GHG Reduction Scenario (**R1**) was developed to the following general principles:

- It was designed to achieve White Paper’s 60% GHG reduction target (on 1990 levels) for transport excluding maritime shipping by 2050, and goal of 40% reduction in maritime shipping GHG (on 2005 levels)
- Lower conventional fuel prices were used which are consistent with the White Paper’s Impact Assessment Global Decarbonisation Scenario (provided by the Commission). A degree of rebound (in activity and increased vehicle energy consumption) resulting from these lower prices was factored into the calculations;
- 2050 targets were assumed to be achieved through predominantly technical measures, plus additional measures broadly consistent with other White Paper Goals (e.g, internalising of external costs, additional shift of road freight transport to rail/IWW)

These scenarios are in line with the BLUE Map scenario and therefore will be used in conjunction with the BLUE Map scenario. This scenario was further modified by using a scenario sensitivity **R2** for the R1 core scenario This scenario explores the potential impact on the core R1 scenario of low GHG saving from biofuels. In the scenario tool the average GHG performance of liquid fuels is determined by the percentage GHG reduction (versus conventional fuels) and percentage deployment/substitution. The default assumptions previously used were for high levels of GHG savings (up to 85% by 2050) and with deployment capped at a fixed maximum amount of up to 174 Mtoe sustainable biofuel by 2050. The scenario findings indicated that there is significant uncertainty as to what the volumes of sustainable biofuel may be available in the future and the net savings (e.g. due to indirect land use change issues). Therefore, the scenario assumes that low savings based on an assessment of potential net savings in the absence of further action from the EC’s draft impact assessment of ~10 - 20% due to indirect land use change (ILUC) impacts

End use sectors

Construction:

For buildings, the annual added m2 per habitable floor space in the EU coupled with the steel demand per m2 of habitable floor space will provide the annual steel demand for buildings.

The steel demand for roads and railway tracks can be calculated by investigating the projected km of roads and railway tracks and multiplying that by the steel required per km of road and railway track.

Transport:

Projecting the number of annual LDV and HDV sales along with vehicle weight reduction potentials and coupling that with the steel intensity per vehicle will provide the annual projected steel demand

Machinery, tubes and appliances:

It is difficult to project the future steel demand up to 2050 for these end sectors due to the lack of literature and available data. Therefore, a simpler approach will be undertaken. Relation between historical demand and population growth will be investigated. Another approach would be to investigate the yearly increase or decrease of steel demand for these sectors.

Wind and Solar PV:

Projected added capacity based on IEA BLUE map scenarios coupled with the steel intensity per MW of added capacity will provide the annual steel demand for this sector

Steel Grades

Investigating the steel demand in these end use sectors will help in identifying the major grades of steel used in these sectors. According to the World Steel Association, there are over 3,500 different grades of steel, encompassing unique physical, chemical, and environmental properties.

In essence, steel is composed of iron and carbon, although it is the amount of carbon, as well as the level of impurities and additional alloying elements that determine the properties of each steel grade. The use of scrap for different steel grades depends on amount of residual elements present. Higher steel grades usually require lower amounts of residual elements than are present in scrap steel ((Pretorius, Oltmann & Jones). Due to time constraints and for simplicity for this research, these wide variety of grades will not be investigated. Instead two basic classifications will be made.

- High grade: steel grades that will be produced using BF-BOF process using 25% scrap
- Low grade: steel grades that can be produced using EAF process using 100% scrap

Production Route

The above analysis will provide information on the preferred production route (BF-BOF or EAF) as BF-BOF route produces higher grade steel using primary iron with low scrap input while the EAF route produces lower grade steel using scrap

The next step will be to create a dynamic stock model using the above information to predict the amount of primary iron and scrap required for the steel products used in the key sectors.

Once the preferred production routes are known, the CO_2 emissions for these routes can be calculated for future steel demand by investigating existing literature on emissions for current steel production technologies.

The next step is to provide recommendations on future production technologies to further reduce CO_2 emissions to meet 2050 target. Literature and studies which are in line with the BLUE Map scenario will be used to investigate these future production technologies.

Results

The BLUE map scenario (IEA, 2009, 2010) detailed in the in the methodology chapter will be used as a basis to help project EU steel demand till 2050.

For transport related projections, the **R2** (low biofuel GHG savings) sensitivity for the core **R1** scenario from the SULTAN (Sustainable Transport) illustrative scenario tool will be used.

The R2 scenario sensitivity was used since the share of fuel cells (FCEV) and electric vehicles (EV) sales in 2050 is expected to dominate the market (IEA, 2009, 2010). This means that biofuels will be used as a transitional fuel till FCEV and EV become competitive from a technical and economic viewpoint.

End Use Sector:

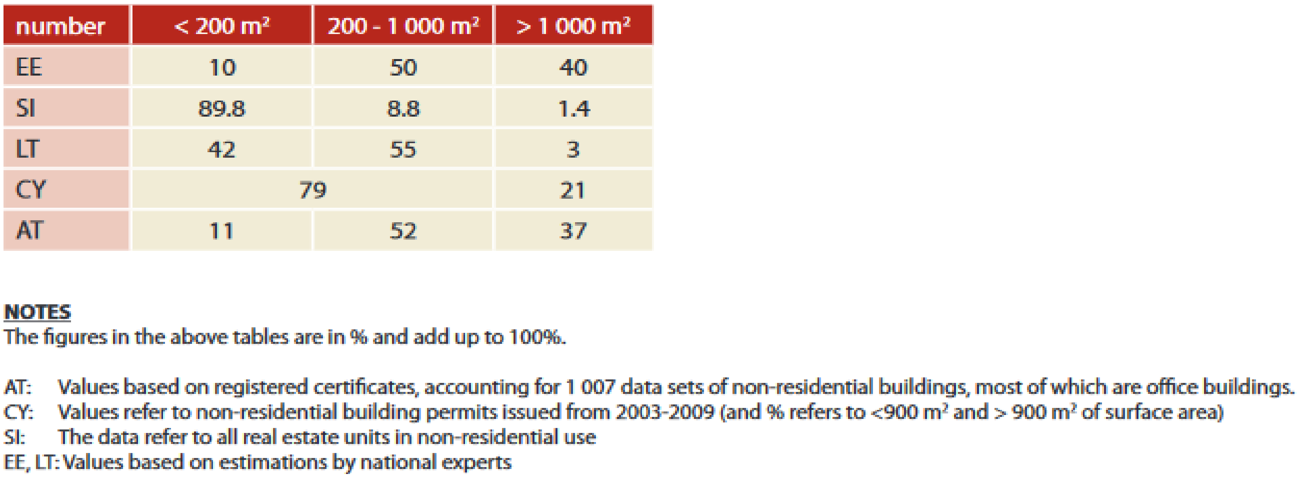
Construction

Constructions accounts for a major share of the EU steel demand. In 2016 it accounted for 35% of the EU steel demand (EUROFER, 2016). Construction encompasses residential and non-residential buildings, roads, railway tracks, bridges and power production facilities but for this research, residential and non-residential, roads and railway tracks will be investigated. Among power production facilities, wind and solar PV will be investigated since renewables are expected to have a major share in power production by 2050 (IEA, 2013). Wind and PV has been identified as a separate end use sector as it will be interesting to know the projected steel demand in the EU for the renewable sector.

Residential and non-residential buildings

According to the IEA *Energy Technology Transition for Industry (*2009), achieving the outcomes in the BLUE Map scenario will require significant changes in standards for buildings constructed till 2050 and in the transformation of existing building stock. In the BLUE Map scenario, all residential buildings in cold- climate countries need to meet equivalent of passive house energy requirements (15kWh.m2/year for heating, cooling and ventilation). Therefore, refurbishments will be an integral part of future buildings.

The projected residential building stock in the EU by 2050 is 240 million dwellings (IEA, 2009). Non-residential buildings currently account for 25% of the total building stock (BPIE,2011). Using the same share, the projected total building stock for 2050 will be 320 million dwellings (240 million residential, 80 million non-residential). Using a 75-year life time for buildings (Pauluik, 2013), the yearly added building stock was calculated. The average m^2 of habitable floor area per dwelling in the EU is around 80 m2 and residential (BPIE,2011). Non-residential dwellings are composed of offices, retail and wholesale, hospitals, sports facilities, educational buildings and hotels & restaurants (BPIE,2011). The m2 per habitable floor area varies for these facilities (BPIE,2011). Figure (6) provides the range and percentage of m2 of habitable floor area used by these facilities. The CY source is used since values refer to non-residential building permits issued from 2003-2009 (and % refers to <900 m and > 900 m of surface area) (BPIE,2011). A weighted of these values were taken to calculate the average m^2 of habitable area per non-residential dwelling.



number	< 200 m²	200 - 1 000 m²	> 1 000 m²
EE	10	50	40
SI	89.8	8.8	1.4
LT	42	55	3
CY	79		21
AT	11	52	37

NOTES
The figures in the above tables are in % and add up to 100%.

AT: Values based on registered certificates, accounting for 1 007 data sets of non-residential buildings, most of which are office buildings.
CY: Values refer to non-residential building permits issued from 2003-2009 (and % refers to <900 m² and > 900 m² of surface area)
SI: The data refer to all real estate units in non-residential use
EE, LT: Values based on estimations by national experts

Figure 6: m2 average m2 floor area for nonresidential buildings

Source: BPIE, 2011

The steel intensity (kg steel/m^2 of habitable floor area) for buildings is in the range of 10 -70 kg steel/m^2 of habitable floor area (IEA, 2009). This averages out to 40 kg steel/m^2 of habitable floor area or 0.04 t steel/ m^2 of habitable floor area. Since refurbishments will be an integral part of the building industry, the BLUE Map scenario projects 20% of the total steel demand for buildings to be associated with refurbishments. The results are provided in table (1)

Table 1: Yearly steel demand for buildings till 2050

	2050
Total stock (residential +non-residential)	320 Million (IEA, 2009)
Yearly added stock	4.2 Million
M^2/dwelling	80 (Residential); 450 (79%), 900 (21%) (non-residential)
T steel/m^2	0.04
Yearly steel demand for new built	33.5 Mt/yr

Yearly steel demand (new built +refurbishments)	41.8 Mt/yr

Roads and Railway tracks

The SULTAN tool **R2** scenario was used to project the km of roads and railway tracks demanded to meet transport. The US interstate highway in 2006 was 73,000 km (USGS, 2006). The material composition of the highway (in Mt) is provided in figure (7)

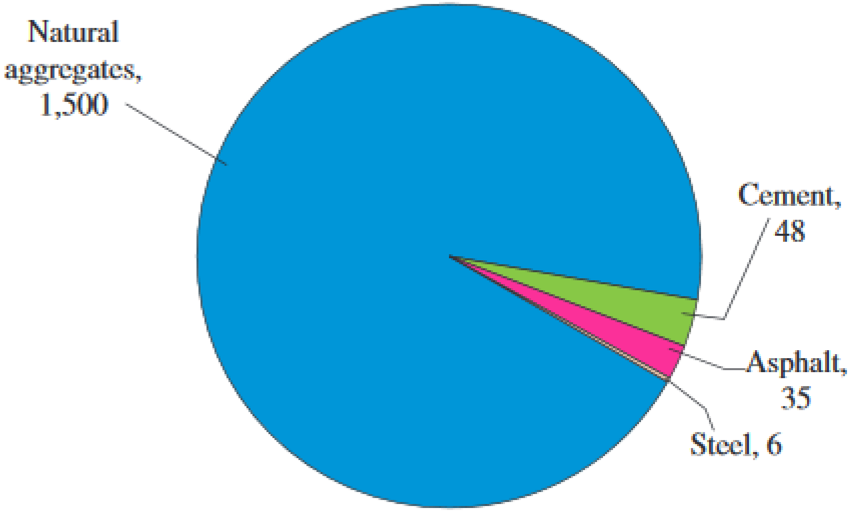


Figure 7: Material demand for US interstate highways

Source: USGS (2006)

Therefore, the average amount of steel used of roads is 82.2 t steel/ km. The average amount of steel used for railway tracks is 50 t steel/km (Madler, Zoll, Heyder, Brehmer). Figure (8) and (9) show the projected km for roads and railways and the steel demand.

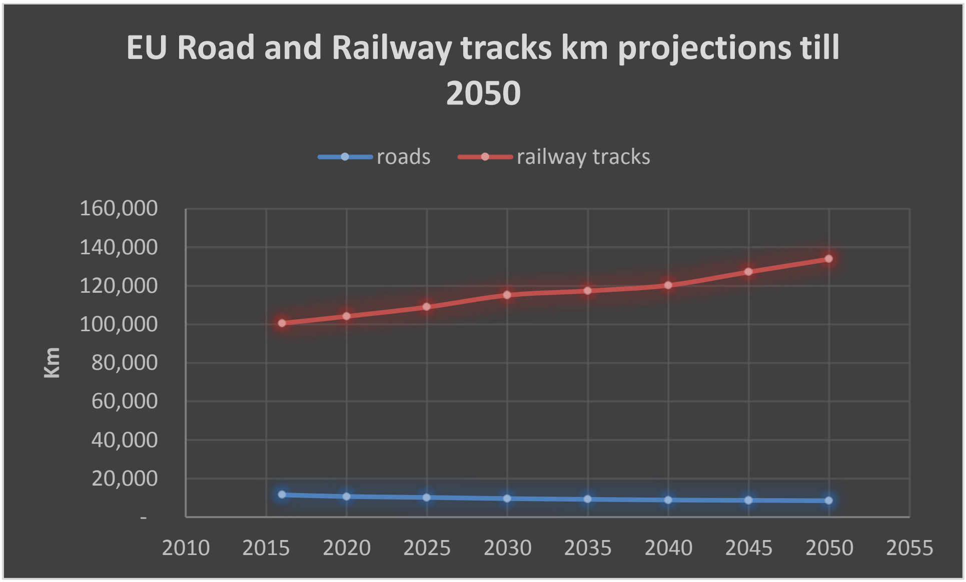


Figure 8: km of roads and railways projection for the EU

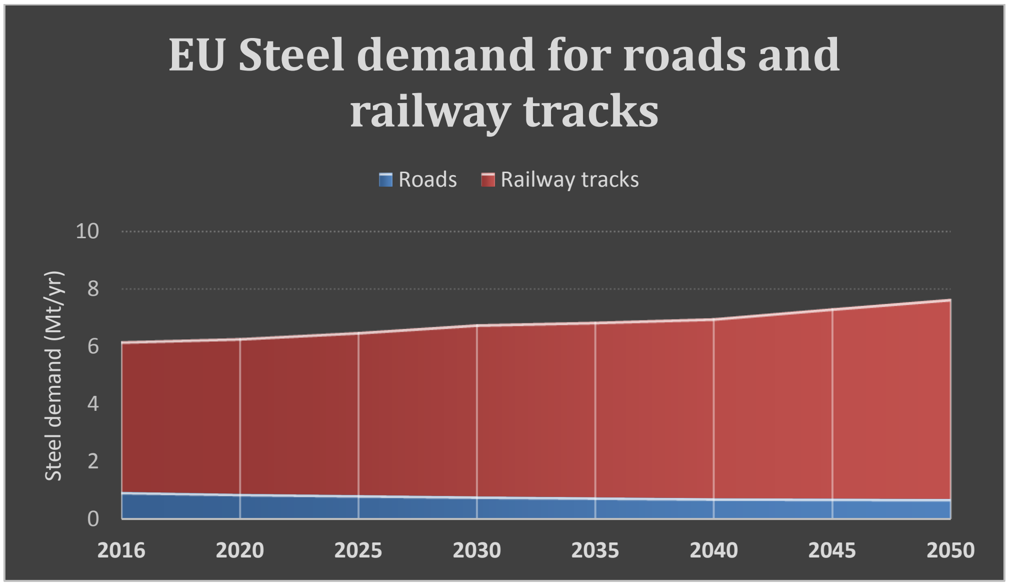


Figure 9: EU steel demand for roads and railway tracks

The km of roads decreases while the km of railway tracks increases since the scenario expects that after 2025, passenger commuting via train will overtake the use of individual cars as they will be more cost effective and efficient. From a CO_2 abatement perspective, this will reduce the emissions due to the decrease use of individual cars and increase in the use of public transport like trains.

In the BLUE Map scenario, some of the expected future growth in passenger travel and freight transport is shifted from LDVs, trucks and air travel into bus and rail travel. In this scenario, global emissions in 2050 are about 3 Gt CO_2-eq lower than in the Baseline scenario defined by the IEA (IEA, 2010)

Figure (10) provides the total steel demand for the construction (residential & non-residential, roads and railway tracks) sector from 2016 to 2050

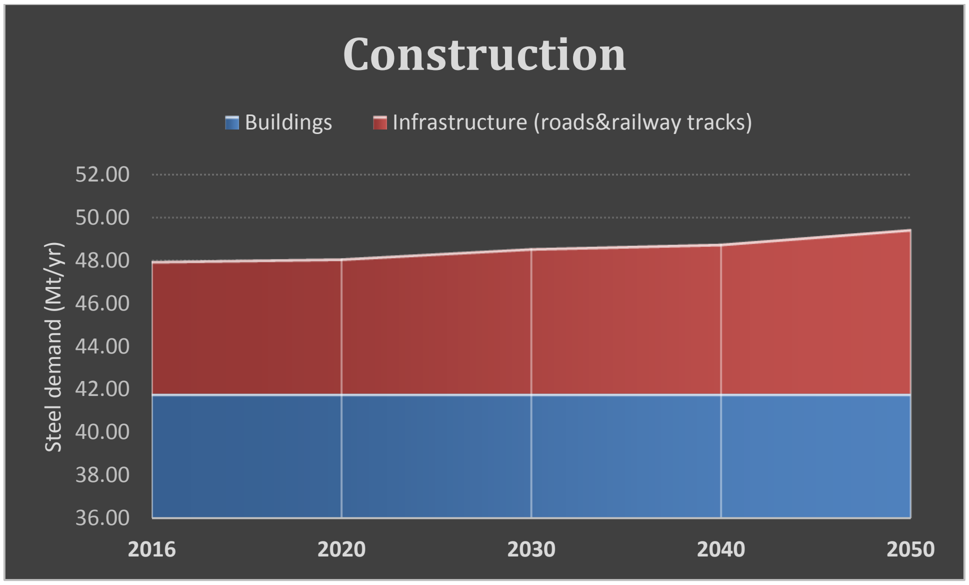


Figure 10: EU steel demand for the construction sector

Steel demand for the construction sector increases from 47 Mt in 2016 to 49 Mt in 2050. Steel demand for buildings remains constant due to the calculation method specified in the methodology. The 2 Mt increase can be attributed to the increase in railway tracks as passenger and freight travel is expected to shift to rail travel.

Transport:

The transport sector can be divided in light duty vehicles (LDV) and heavy duty vehicles (HDV) The SULTAN **R2** scenario described in the methodology chapter was used for LDV and HDV sales projection till 2050. Figure (11) shows the projected LDV sales in the EU till 2050

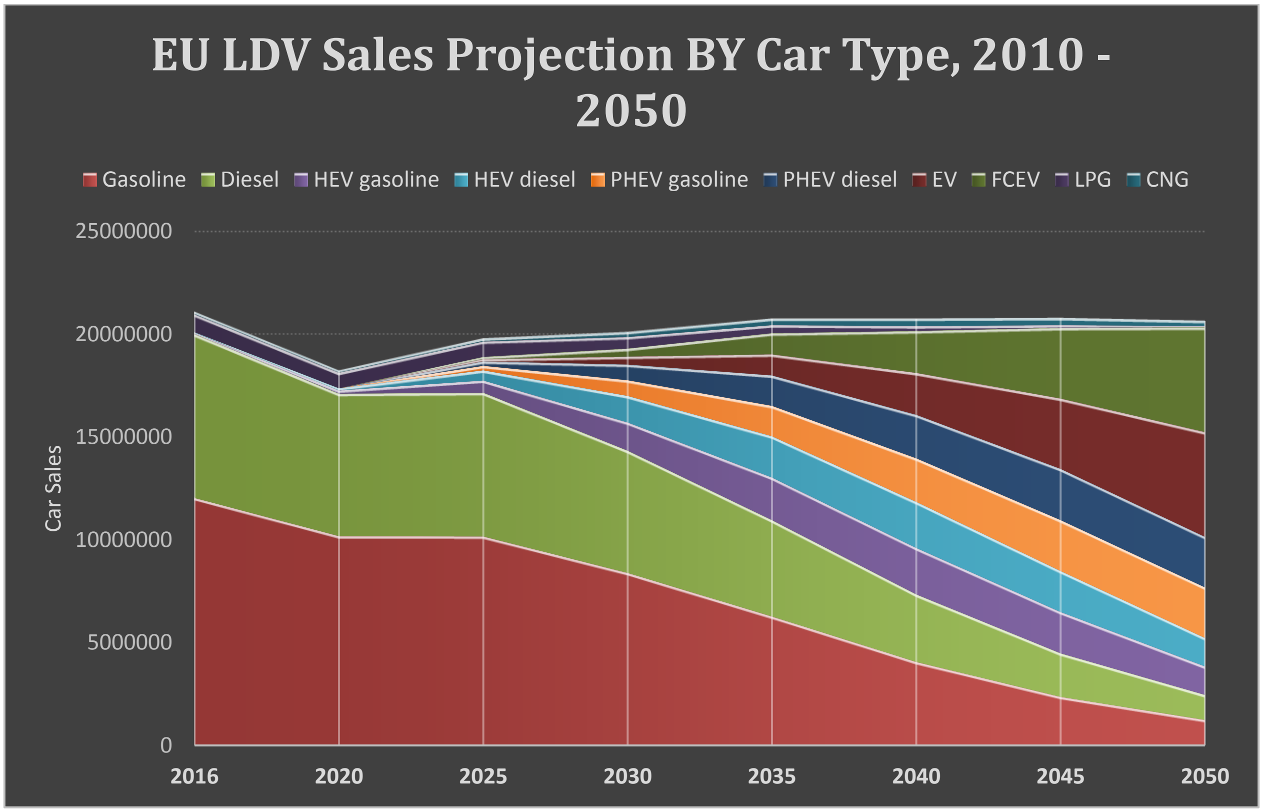


Figure 11: LDV sales projection by car type (based on R2 scenario)

The projected car sales in the EU till 2050 is around 20 Million cars per year with minimal change but the change can be seen in the type of LDV sold. The share of gasoline and diesel vehicles greatly decreases form 2025 as they are replaced with hybrid and plug in hybrid vehicles. Post 2030 the share of EV and FCEV increases as it replaces hybrid and plug in hybrid vehicles due to its light weight and CO_2 abatement potential. Technical development of large scale commercial use of FCEV and EV is predicted to be achieved by 2030 (*EU Transport GHG: Routes to 2050 II*, 2012). The *EU Transport GHG: Routes to 2050 II* report proposes that people will use FCEV and EV's for short distance travel while public transport like trains will be used for long distance travel.

In the BLUE Map scenario, total transport fuel use too rises slowly, reaching 30% above 2007 levels by 2050, with very low-carbon fuels such as electricity and hydrogen (H2) providing more than half of all fuel use in that year. This results in emissions reductions of 9.5 Gt CO_2-eq, about 60% below the Baseline scenario and nearly 20% below 2005 levels (base year for CO_2-eq emissions reduction target in the BLUE scenario) (IEA, 2010)

The steel content of different LDV's are expected to reduce as vehicles are assumed to become lighter over time as high strength steel (UHSS) and aluminum are increasingly used to replace conventional ferrous metals (IE, 2009). Table (2) provides the steel content reduction potentials for the different LDV's

Table 2: LDV weight reduction potential from 2020 to 2050.

LDV Type	2016 (kg/car)	2020 (kg/car)	2030 (kg/car)	2050 (kg/car)
Gasoline	580	500	420	390
Diesel	950	790	630	560
HEV gasoline	600	540	480	390
HEV diesel	790	700	610	570
PHEV gasoline	600	540	480	390
PHEV diesel	790	700	610	570
EV	470	430	390	280
FCEV	400	300	200	150

Source: IEA (2009)

Using the car sales projection in Fig (11) and the steel reduction potential in table (2), the steel demand projections for LDV's can be calculated. Fig (12) provides the steel demand projections for LDV's till 2050.

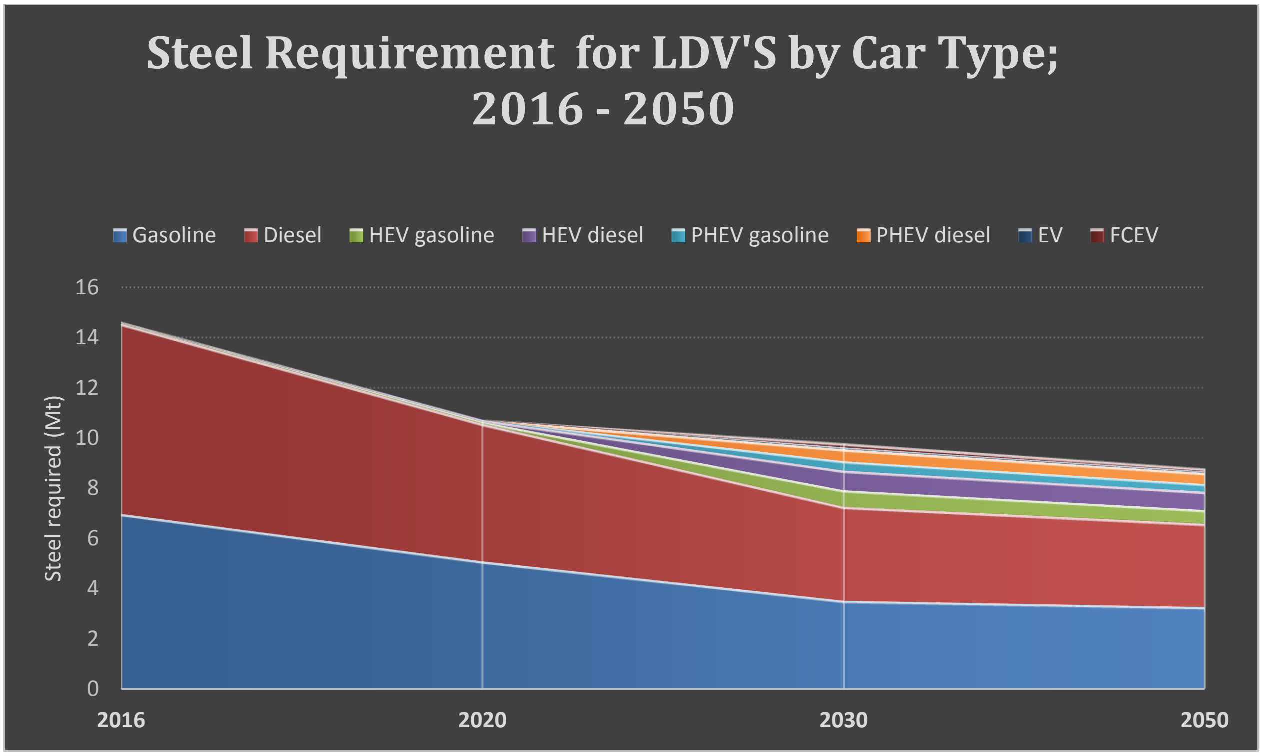


Figure 12: Steel demand for LDV by car type (R2 scenario)

The overall yearly steel demand for LDV’s decreases from 15 Mt in 2016 to 8.9 Mt in 2050. Since gasoline and diesel vehicles dominate the market in 2016, most of the steel demand can be attributed to it. With vehicle weight reduction potential in the future and the increase in share of FCEV and EV which are much lighter than gasoline and diesel vehicles, the steel demand for LDV’s will reduce compared to its current levels.

Figure (13) provides the sales of HDV (Medium and heavy trucks, buses and freight vans)

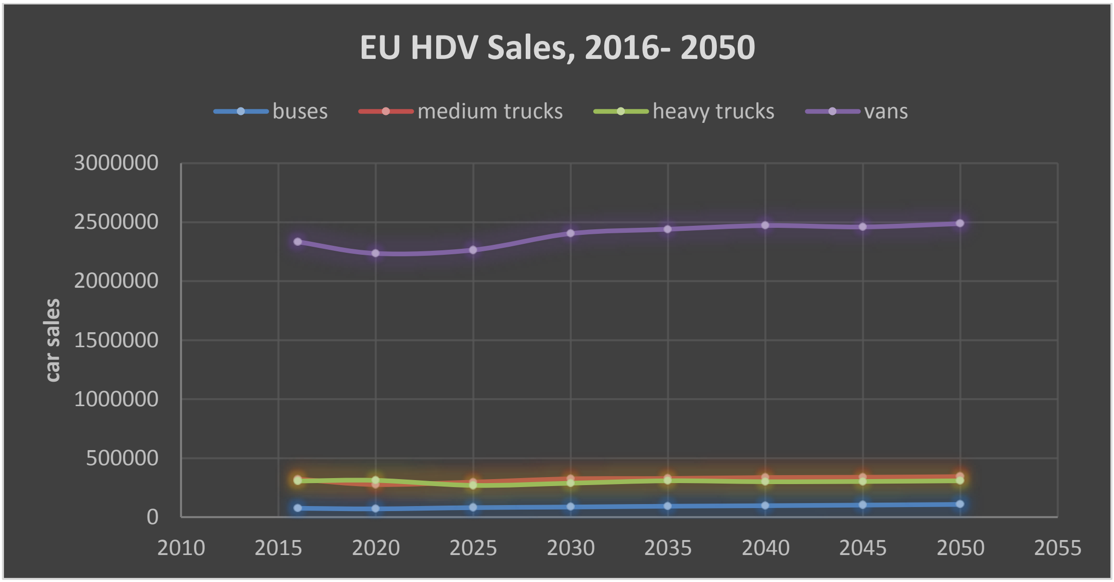


Figure 13: HDV sales projection in the EU (R2 scenario)

Like LDV, HDV too undergo weight reduction with the use of high strength steel. Steel content for buses and freight vans are similar to trucks, so therefore the same steel content reduction potential was used as according to the R2 scenario (*EU Transport GHG: Routes to 2050 II*, 2012) and the BLUE Map scenario weight reduction will also occur in HDV's (IEA, 2010).

Table (3) provides the reduction potential for heavy and medium trucks (U.S Department of Energy, 2013)

Table 3: HDV weight reduction potential

	Steel content reduction			
	2020	2030	2040	2050
heavy and medium trucks	7%	22%	27%	31%

SOURCE: U.S Department of Energy (2013)

Freight vans have similar specifications (Dry Van: Tandem axle L 45 ' x W 8'6"; Smallest inside dimensions L 44'xW8'2"xH8'5") (CME Transportation Best Practices, 2003) as heavy trucks therefore the same steel content was used. Buses are considered to be smaller than heavy trucks and larger than medium trucks (*EU Transport GHG: Routes to 2050 II*, 2012). Therefore, an average steel content of 2.5 t steel/bus is used.

Table 4: Steel intensity per HDV

	Steel content (t steel/ vehicle)	Source
Heavy trucks	3.2	(Schnatterly, 2012)
Medium trucks	2.065	(Schnatterly, 2012)
Freight Vans	3.2	
Buses	2.5	

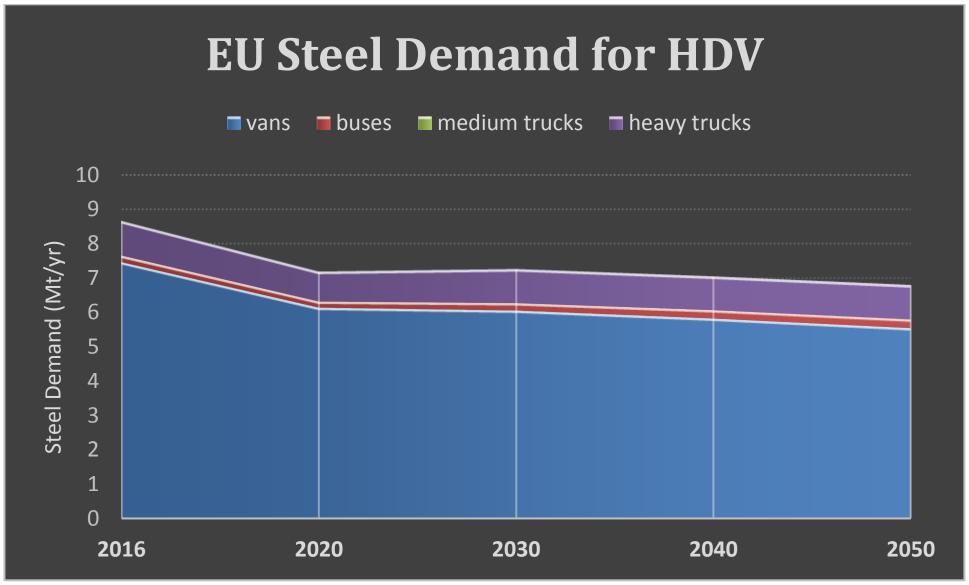


Figure 14: Steel demand projections for HDV

Steel demand for HDV is much lower than for LDV due to the lower number of sales of HDV. Steel demand for HDV reduces from 8.7 Mt in 2016 to 6.8 Mt in 2050. The steep decrease in steel demand from 2016 to 2020 is due to the decline in freight van sales between 2016 to 2020. Freight van sales increase after 2020 as more freight goods are expected to be transported due to increase in population thereby increase in demand for goods (*EU Transport GHG: Routes to 2050 II*, 2012; IEA, 2010).

Figure (15) shows the total steel demand for the transport sector from 2016 to 2050

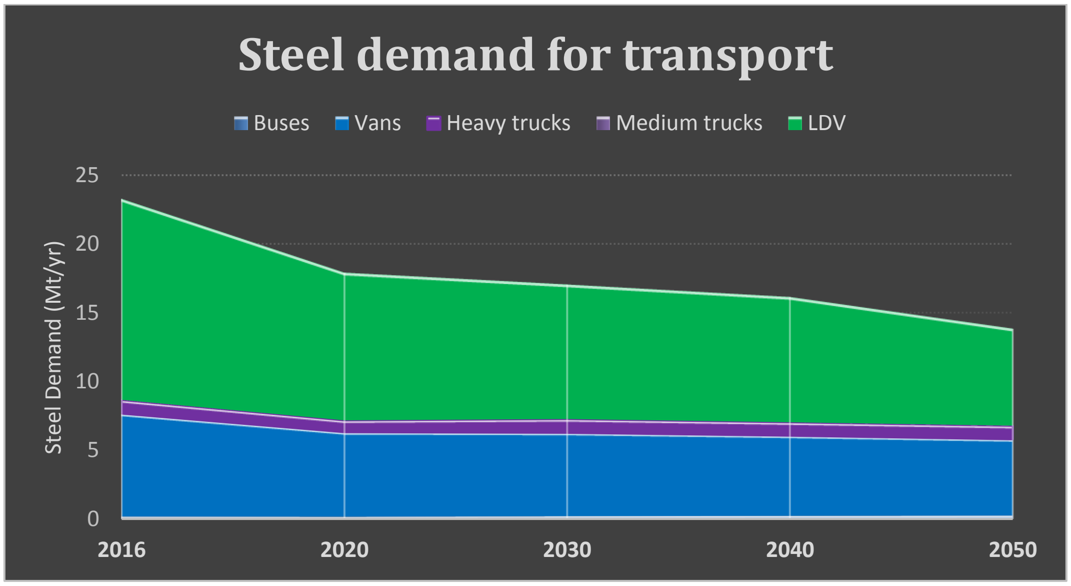


Figure 15: Total EU steel demand for the transport sector

Steel demand in the transport sector is dominated by LDV due to the high amount of car sales. Steel demand decreases from 23 Mt in 2016 to 13.8 Mt in 2050. This decrease can be attributed to vehicle weight reduction potential for the different vehicles and the rapid growth of light weight FCEV and EV from 2030.

Wind and Solar PV.

Wind

In order to reduce carbon emissions by 2050, the European Commission has targeted 50% power production from wind (EWEA). The plan is to have 20%, 33% and 50% wind power in 2020, 2030 and 2050 respectively. Table (5) shows the plan envisaged by the EWEA to meet that goal.

Table 5: Expected EU wind capacity projection till 2050

year	% of total power production	capacity	
2020	20%	265	210 onshore
			55 offshore
2030	33%	400	250 onshore
			150 offshore
2050	50%	150	250 onshore
			350 offshore

Source EWEA

Wind turbines usually have a lifetime of 20 years (IEA, 2010) after which they are decommissioned. The decommissioned capacity needs to be added along with new capacity built, in order to maintain stable power generation. For example: capacity added in 2030 will be decommissioned in 2050 and needs to be added again in 2050 along with new capacity built. The added capacity was calculated using table (5) and figure (16) provides the added capacity for wind turbines in the EU from 2016 to 2050.

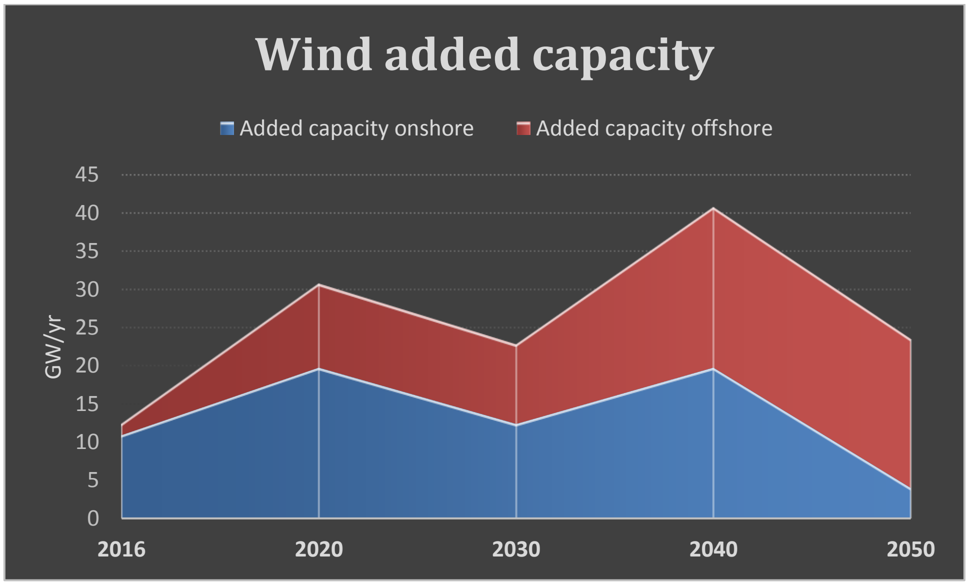


Figure 16: Projected added wind capacity in the EU

Between 2016 and 2020 there is a rapid increase in added capacity to meet 2020 goals of 22% wind generation. Post 2020, capacity is added at a slower rate and after 2030 capacity is increased to meet 2050 target of 50 % wind energy generation. Onshore installations decrease while offshore installations increase due to lack of available space to install onshore and due to the higher generation of power from offshore (IEA, 2010; EWEA).

Figure (17) provides the steel demand per MW of installed capacity

	Steel demand (t/MW)	Source
wind onshore	203	McVeigh & Ancona, (2001)
wind offshore	290	McVeigh & Ancona, (2001)

Figure 17: Steel demand per MW of installed wind capacity

Steel demand for wind turbines can be attributed to the tower, nacelle and rotor, the tower being the major user of steel (World Steel Association). (Figure 18) shows the projected steel demand till 2050 based on the projected added capacity.

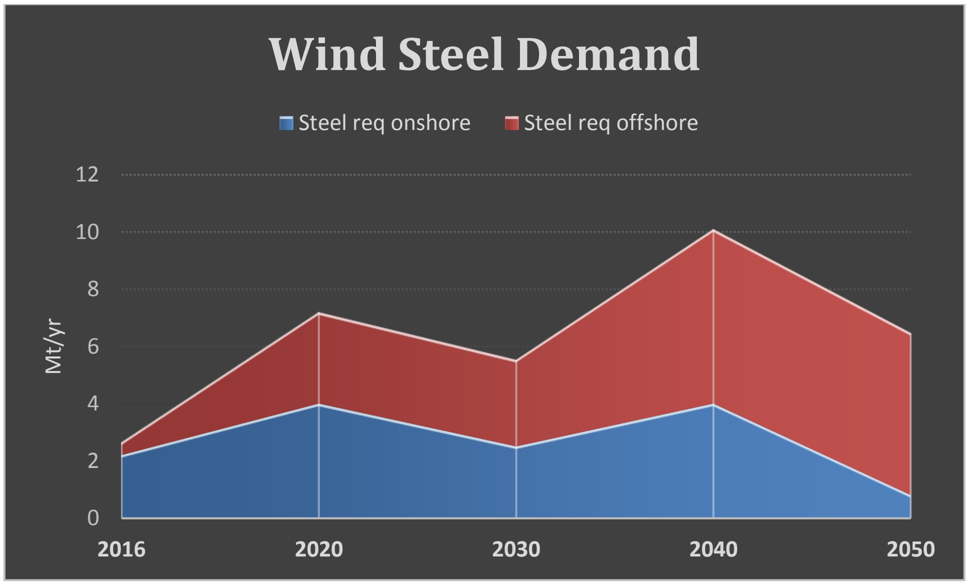


Figure 18: EU steel demand for wind

Steel demand for wind increases from 2.8 Mt in 2016 and peaks at 10 Mt in 2040. Since the rate of offshore installations will rise between 2030 and 2040 to meet the EU 2050 goal, a peak in demand can be seen in 2040 since the 19.75 GW (onshore) and 11 GW (offshore) added capacity in 2020 needs to be decommissioned in 2040 and added back to the grid.

PV.

According to the IEA's Energy Technology Perspective (ETP) report (2014) which is in line with the BLUE Map scenario, global emissions from the power sector should reach a mere 1 Gt CO_2 by 2050 with PV avoiding 4 $GtCO_2$/yr or 19% of the whole power sector emission reduction. Figure (19) shows the regional production from PV envisioned in the ETP, 2014 roadmap.

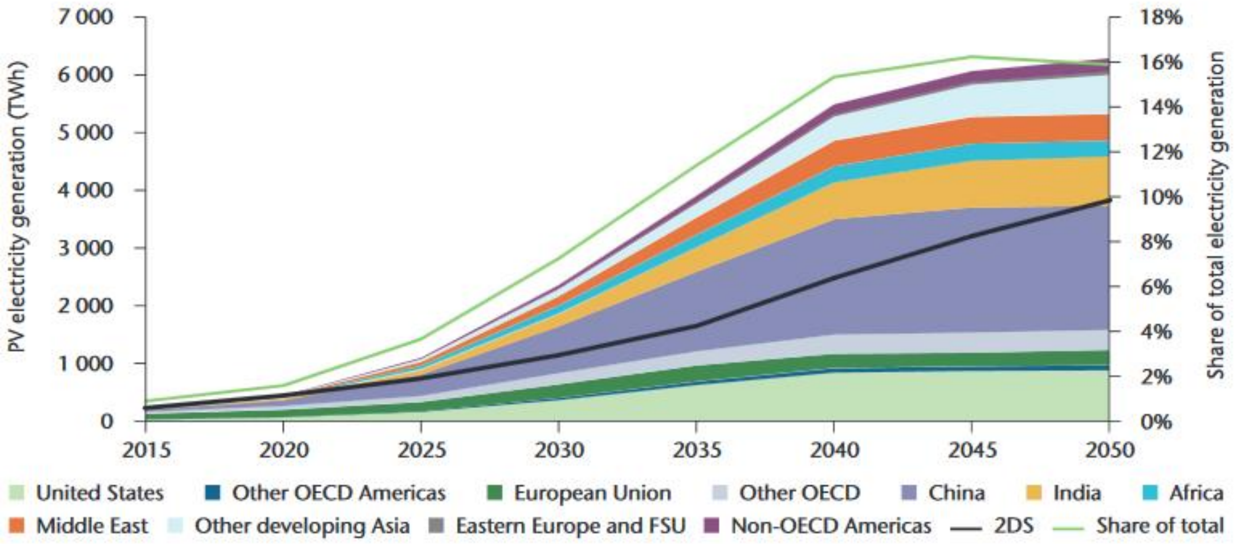
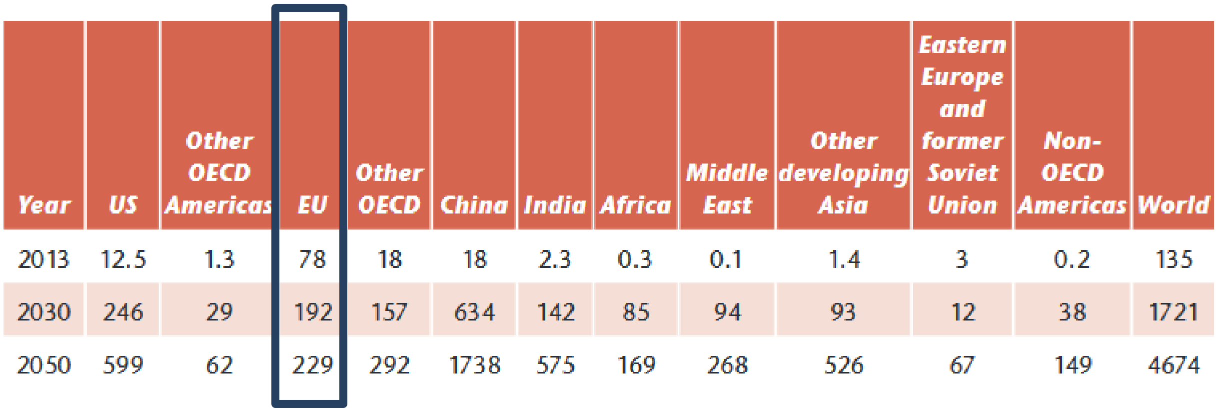


Figure 19: Regional projected share of PV electricity generation till 2050

Source: IEA (2014)

The EU will account for about 1% of the global PV power generation and 8% of the EU total power generation mix (IEA, 2014). In Europe, the solar resource is high in the south but significantly lower in the north, while electricity demand is on average greater in winter than in summer (IEA, 2011). Demand peaks often occur in late afternoon or early evening, so the "capacity credit" of PV at winter peak times is close to zero in most countries. Wind power in Europe offers a better match with daily and seasonal variations in demand, at competitive costs, and thus limits the penetration of PV to about 8% by 2050 (IEA, 2014). Figure (20) shows the roadmap planned by the IEA to achieve the goal



Year	US	Other OECD Americas	EU	Other OECD	China	India	Africa	Middle East	Other developing Asia	Eastern Europe and former Soviet Union	Non-OECD Americas	World
2013	12.5	1.3	78	18	18	2.3	0.3	0.1	1.4	3	0.2	135
2030	246	29	192	157	634	142	85	94	93	12	38	1721
2050	599	62	229	292	1738	575	169	268	526	67	149	4674

Figure 20: Regional projected PV capacity; 2030 and 2050

Source: IEA (2014)

The lifetime of a PV panel is around 20 years (IEA, 2014), therefore capacity added in 2030 will need to be decommissioned and rebuilt in 2050. With a steel intensity of 73 t/MW (IEA, 2009) of installed capacity, the year steel demand for PV can be calculated. Figure (21) shows the added capacity and the steel demand for PV in the EU from 2016 to 2050

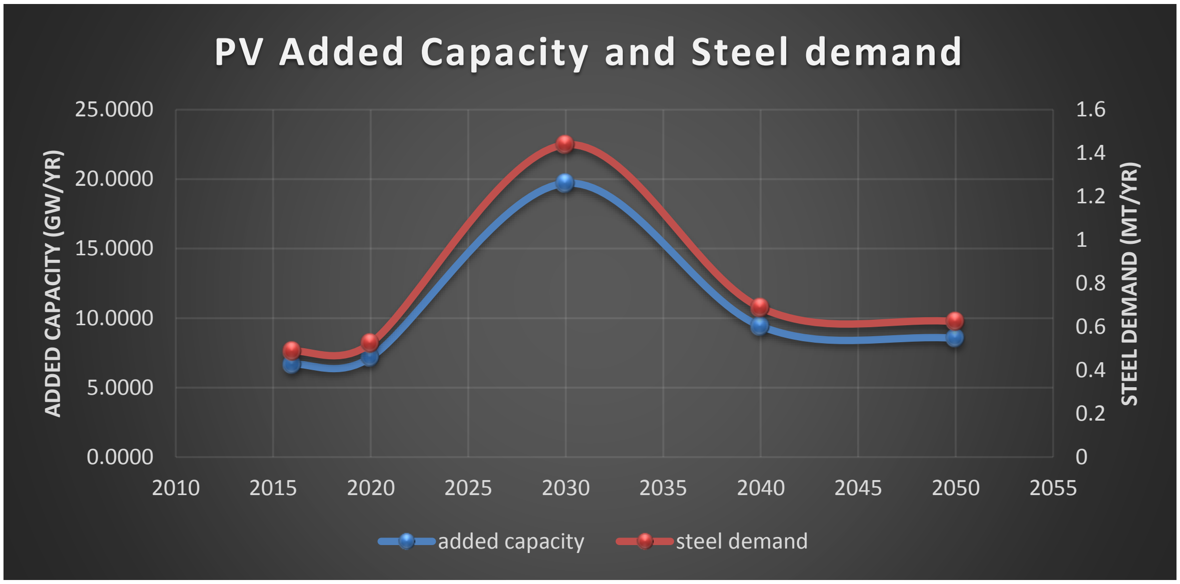


Figure 21: Projected added capacity and steel demand for PV in the EU till 2050

Steel demand peaks at 1.4 Mt in 2030 as steel demand follows capacity addition and the declines post 2030 to 0.6 Mt in 2050. Figure (22) provides the total yearly steel demand for wind and PV

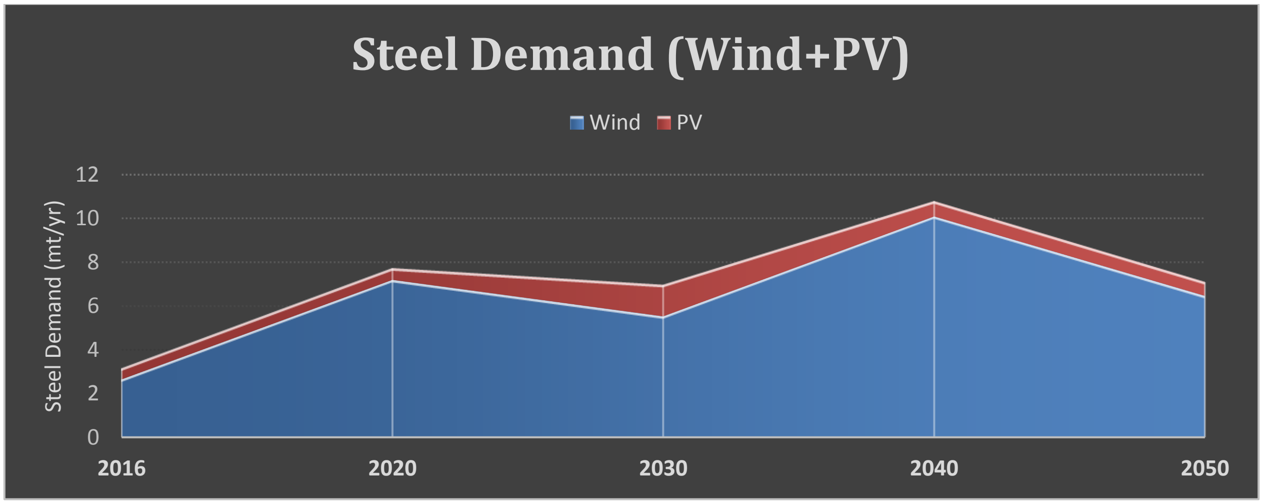


Figure 22: Projected steel demand for wind and PV in the EU

Steel demand for wind and PV increases from 2.5 Mt in 2016 to 7 Mt in 2050 since renewables will need to have a high share of the power sector to meet CO_2 goals set out in the BLUE Map scenario. Steel demand peaks in 2040 due to the increased deployment of offshore wind. Most of the steel demand for renewables can be attributed to wind due to its increased deployment rate and wind turbines require more steel (203- 290 t/MW) than PV (73 t/MW).

Machinery, Tubes, Metal goods and appliances.

Development of these sectors were hard to project till 2050 due to lack of relevant literature and useful data. The IEA BLUE Map scenario does not provide enough information or projections for these sector developments to meet CO_2 targets set for 2050. Therefore, a simple approach is used here.

Trend in steel demand for these sectors for the past 4 years were investigated and then extrapolated to 2050. Table (6) shows the steel demand in the EU for these sectors from 2012 to 2016. (World Steel Association, Steel Statistics)

The % share of total demand remains same for these sectors during the past 4 years (EUROFER, 2016)

Table 6: Steel demand for machinery, metal goods, appliances and tubes in the EU from 2012-2016

	% of total demand	2012	2013	2014	2015	2016
Total (Mt)		168	166	169	166	161
Machinery (Mt)	14%	23.52	23.24	23.66	23.24	22.54
Metal goods (Mt)	14%	23.52	23.24	23.66	23.24	22.54
tubes (Mt)	13%	21.84	21.58	21.97	21.58	20.93
appliances (Mt)	3%	5.04	4.98	5.07	4.98	4.83

Source: World Steel Association

The yearly change in steel demand for these sectors was then averaged over the 4 years. Table (7) shows the average yearly decline in steel demand for these sectors. This average year decline was then used to extrapolate steel demand for these sectors till 2050.

Table 7: yearly decline rate in steel demand

	Average yearly decline in steel demand
Machinery (Mt)	0.25
Metal goods (Mt)	0.25
tubes (Mt)	0.23
appliances (Mt)	0.053

Figure (23) shows the projected steel demand for these sectors from 2016 to 2050 using the yearly decline rate from table (7)

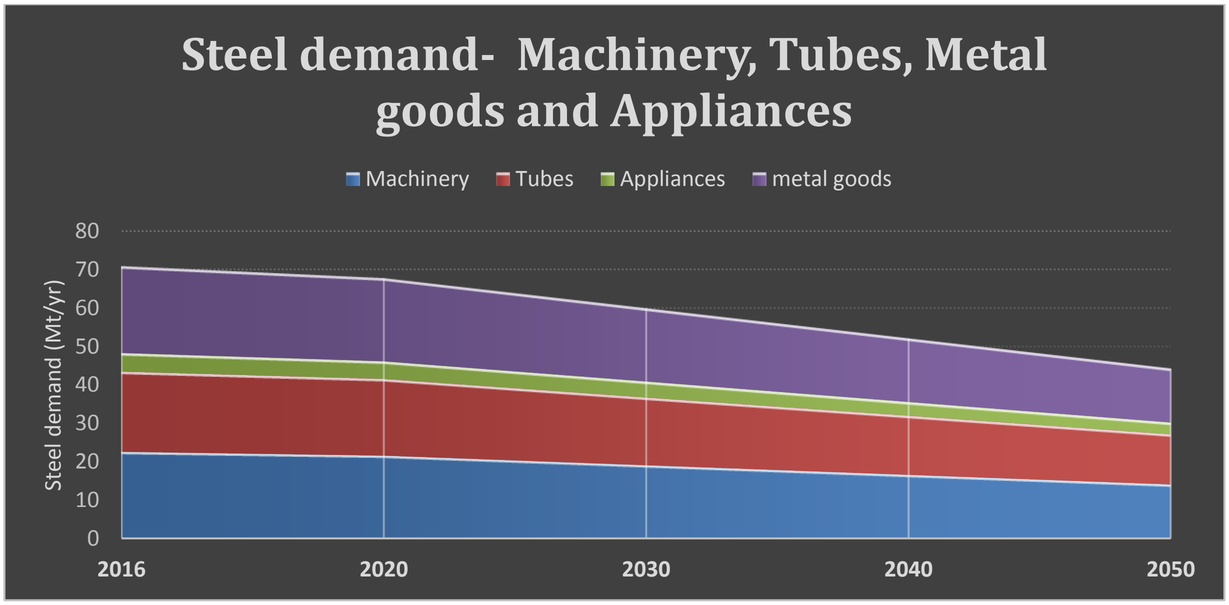


Figure 23: Projected steel demand in the EU for machinery, tubes, metal goods and appliances

Steel demand for these sectors declines form 70 Mt in 2016 to 44 Mt in 2050. Machinery and metal goods decline from 22 Mt in 2016 to 14 Mt in 2050 while appliances and tubes decrease from 4.8 Mt and 20.9 Mt in 2016 to 3 Mt and 13.1 Mt in 2050 respectively. Extrapolating these end use sectors with population growth is not a preferred methodology since he lifetime of these goods is around 15 years (Pauliuk, 2013) and extrapolating demand with population growth ignores stock lifetime (Pauliuk, 2013).

Total sector steel demand

In the previous sub chapter steel demand for the identified end use sectors (construction, transport, wind and solar PV, machinery, metal goods, tubes and appliances) was projected to 2050. Figure (24) shows the total projected steel demand for the all the end use sectors investigated for this research.

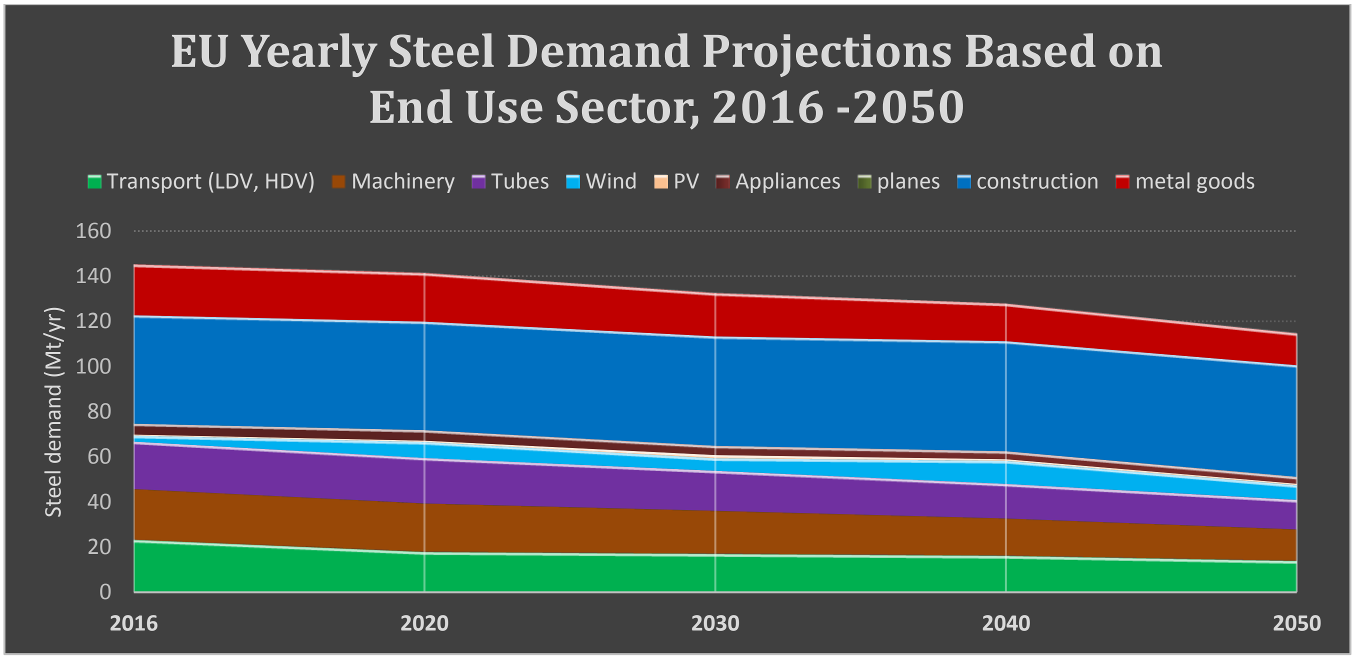


Figure 24: Projected EU total end use sector steel demand

Figure (24) shows that the EU steel demand based on end use sectors decreases from 145 Mt in 2016 to 114 Mt in 2050. According to EUROFER 2016 Market Report, the total steel demanded in the EU in 2016 was 161 Mt. The analysis carried out in this research provides a steel demand of 145 Mt in 2016. The 16 Mt difference can be attributed to miscellaneous and other transport which account for 4% of the total demand in 2016. Steel demand for other power generating technologies like nuclear, coal and natural gas were not considered in this research since renewables are expected to have a major share in power production from 2030 onwards (IEA, 2010). Therefore, the 16Mt difference will be termed as “other” and added to the 2016 steel demand calculated in this research. To simplify the research steel demand projection for the “other” sector will be taken as constant. Figure (25) show the total steel demand for the EU from 2016 to 2050.

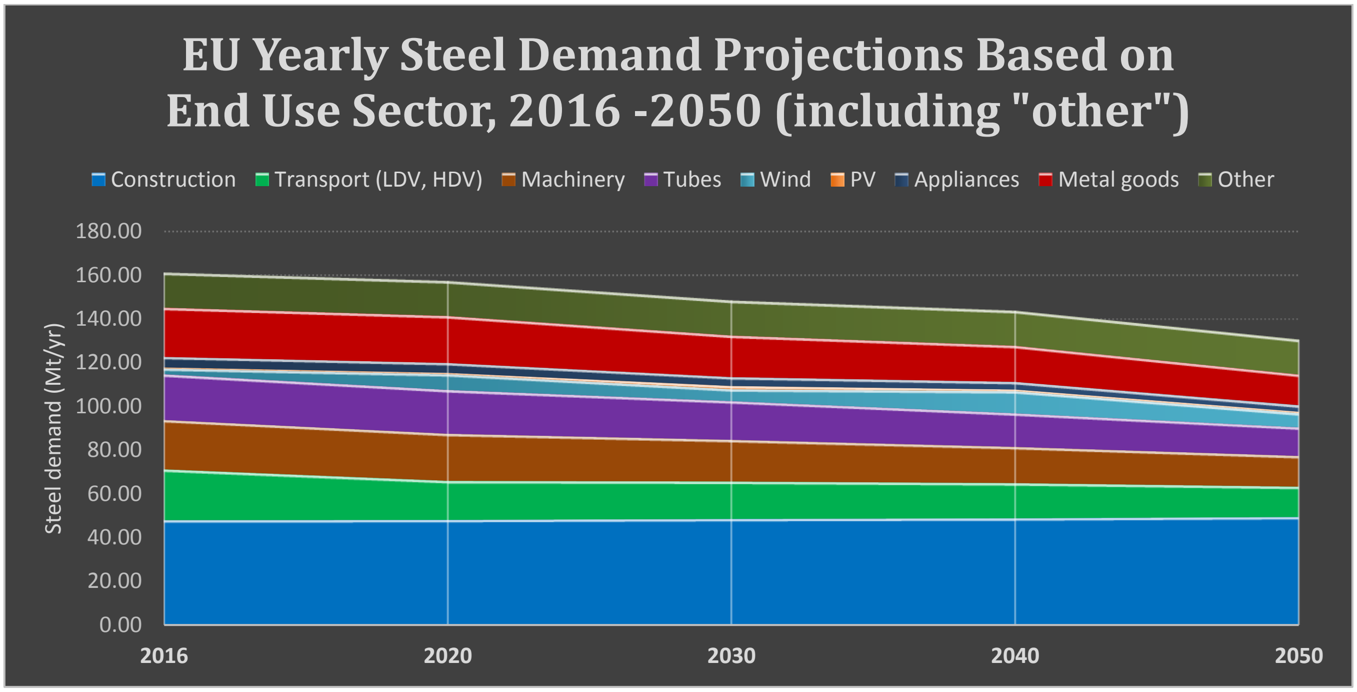


Figure 25: Projected EU total end use sector steel demand including "other"

Based on the end use sector analysis, steel demand in the EU declines from 161 Mt in 2016 to 130 Mt in 2050. Table (8) proves the % share of total demand for each end use sector

Table 8: End use sector share of total steel demand

End Use sector	2016	2020	2030	2040	2050
Construction	30%	31%	33%	34%	38%
Transport (LDV, HDV)	13%	10%	10%	10%	9%
Machinery	14%	14%	13%	12%	11%
Tubes	13%	13%	12%	11%	10%
Wind	2%	5%	4%	7%	5%
PV	0.3%	0.3%	1.0%	0.5%	0.5%
Appliances	3%	3%	3%	2%	2%
Metal goods	14%	14%	13%	12%	11%
Other	11%	11%	12%	12%	13%

All of the sectors show a declining trend in % share of total steel demand except for construction and wind. More capacity for wind will be build post 2030 as it replaces PV in the EU (IEA, 2014). Share steel demand for construction increases due to the decline in the product demanded from the other end use sectors and since steel demand for construction remains relatively stable from 2016 to 2050 (based on calculation method).

Share of steel demand for transport decreases due to the declining share of gasoline and diesel cars and the high penetration of light weight FCEV and EV from 2030 which will be required for the transport industry to meet CO_2 goals for 2050 (IEA, 2009; *EU Transport GHG: Routes to 2050 II*, 2012).

In the next subchapter, the steel grades associated with these end use sectors will be identified and differentiated in High and Low grade steel.

Steel Grades

Different types of steel are produced according to the properties required for their application, and various grading systems are used to distinguish steels based on these properties. According to the American Iron and Steel Institute (AISI), steel can be broadly categorized into four groups based on their chemical compositions:

1. Carbon Steels
2. Alloy Steels
3. Stainless Steel
4. Tool Steels

Carbon Steels

Carbon steels contain trace amounts of alloying elements and account for 90% of total steel production. Carbon steels can be further categorized into three groups depending on their carbon content:

- *Low Carbon Steels/Mild Steels* contain up to 0.3% carbon
- *Medium Carbon Steels* contain 0.3 – 0.6% carbon
- *High Carbon Steels* contain more than 0.6% carbon

Alloy Steels

Alloy steel contain alloying elements (e.g. manganese, silicon, nickel, titanium, copper, chromium and aluminium) in varying proportions in order to manipulate the steel's properties, such as its hardenability, corrosion resistance, strength, formability, weldability or ductility.

Applications for alloys steel include pipelines, auto parts, transformers, power generators and electric motors (World Steel Association)

Stainless Steels

Stainless steels generally contain between 10-20% chromium as the main alloying element and are valued for high corrosion resistance. With over 11% chromium, steel is more resistant to corrosion than mild steel. These steels can be divided into three groups based on their crystalline structure (The American Iron & Steel Institute):

- *Austenitic:* Austenitic steels are non-magnetic and non heat-treatable, and generally contain 18% chromium, 8% nickel and less than 0.8% carbon. Austenitic steels form the largest portion of the global stainless steel market and are often used in food processing equipment, kitchen utensils, and piping.
- *Ferritic:* Ferritic steel contain trace amounts of nickel, 12-17% chromium, less than 0.1% carbon, along with other alloying elements, such as molybdenum, aluminum or titanium. These magnetic steels cannot be hardened by heat treatment but can be strengthened by cold working.
- *Martensitic:* Martensitic steels contain 11-17% chromium, less than 0.4% nickel, and up to 1.2% carbon. These magnetic and heat-treatable steels are used in knives, cutting tools, as well as dental and surgical equipment.

Tool Steels

Tool steels contain tungsten, molybdenum, cobalt and vanadium in varying quantities to increase heat resistance and durability, making them ideal for cutting and drilling equipment (The American Iron & Steel Institute).

Steel products can also be divided by their shapes and related applications:

- *Long/Tubular Products* include bars and rods, rails, wires, angles, pipes, and shapes and sections. These products are commonly used in the automotive and construction sectors.
- *Flat Products* include plates, sheets, coils, and strips. These materials are mainly used in automotive parts, appliances, packaging, shipbuilding, and construction.

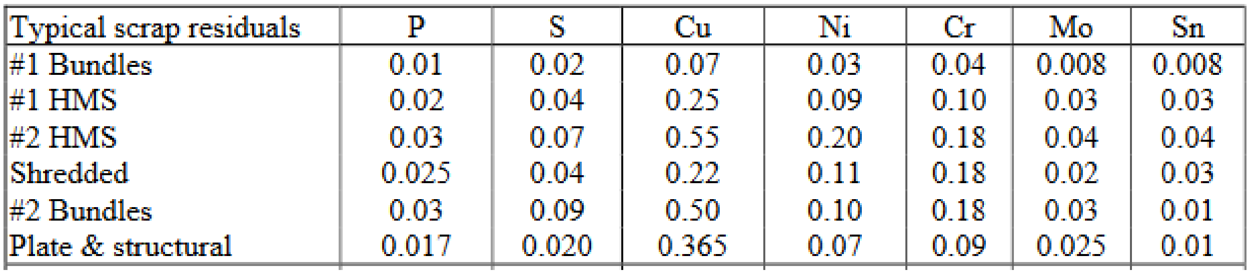
- *Other Products* include valves, fittings, and flanges and are mainly used as piping materials.

To find out the share of high and low grade steel the role of scrap steel needs to be investigated. Scrap steel comes primarily from three main sources (Pretorius, Oltmann & Jones):

1. Reclaimed or obsolete scrap – Scrap material arising from materials beyond useful life including old cars, demolished buildings, discarded machinery and domestic objects.
2. Industrial or prompt scrap – Ferrous scrap material from manufacturing operations for immediate disposal.
3. Revert or home scrap – scrap generated during steel making process, eg. Crop ends from rolling operations, metallic losses in slag, etc.

The latter two are close in chemical composition to the desired molten steel composition and thus ideal for recycle. Reclaimed/obsolete scrap often has quite variable composition and quite often contains contaminants that are undesirable for steel making. (Pretorius, Oltmann & Jones,). Reclaimed/obsolete scrap is more available than industrial/ scrap.

The most important chemical aspects of scrap are the residual elements which include Cu, Sn, Ni, Cr, Mo. The levels of these elements must be below specific limits for certain steel grades since they can affect the product quality and casting operations (Pretorius, Oltmann & Jones,). Figure (26) shows the residual levels of different scrap types



Typical scrap residuals	P	S	Cu	Ni	Cr	Mo	Sn
#1 Bundles	0.01	0.02	0.07	0.03	0.04	0.008	0.008
#1 HMS	0.02	0.04	0.25	0.09	0.10	0.03	0.03
#2 HMS	0.03	0.07	0.55	0.20	0.18	0.04	0.04
Shredded	0.025	0.04	0.22	0.11	0.18	0.02	0.03
#2 Bundles	0.03	0.09	0.50	0.10	0.18	0.03	0.01
Plate & structural	0.017	0.020	0.365	0.07	0.09	0.025	0.01

Figure 26: Typical % of residual elements present in scrap steel

Source: Pretorius, Oltmann, Jones

Therefore, the ability for scrap steel to meet high grade steel depends on the amount of residual elements present. EAF usually produce high alloyed steels, mainly stainless steel and lower quality grade long products directed into construction industry (Janke, Savov, Weddige, Schulz, 2000)

Therefore, for this research high grade steel will use minimal scrap while low grade steel can be met with 100 % scrap

Construction: the prime requirement of construction steels is to meet specific mechanical properties at the lowest possible price. The steels are therefore characterized by their guaranteed tensile strength in MPa (Fe 360) or their guaranteed yield strength in MPa (Fe E250). Usually their tensile strength does not exceed 500 MPa. These steels need to be protected against corrosion either by organic layers (paints) or by a metallic layer (zinc) (World Steel Association). These steels can often be ordered in a coated form. They are low cost, general purpose steels which have excellent welding characteristics. They are usually less suitable for machining.

For railway tracks rail steel is required. These are subject to very high loads and extreme wear stresses. The principle cause of rail degradation are side and vertical wear, rolling contact fatigue and defects such as squats (TATA steel, 2014). Therefore, high strength steel will be required for railway tracks.

Transport: According the BLUE Map scenario vehicles ae assumed to become lighter over time as high strength steel and aluminium are increasingly used to replace conventional ferrous metals (IEA 2009). Therefore, Ultra High Strength Steel will be deployed for the automotive industry. Advanced High-Strength Steels (AHSS) are complex, sophisticated materials, with carefully selected chemical compositions and multiphase microstructures resulting from precisely controlled heating and cooling processes. Various strengthening mechanisms are employed to achieve a range of strength, ductility, toughness, and fatigue properties (World Auto Steel).

Steels with yield strength levels in excess of 550 MPa are generally referred to as AHSS. These steels are also sometimes called “ultrahigh-strength steels” for tensile strengths exceeding 780 MPa. AHSS with tensile strength of at least 1000 MPa are often called “GigaPascal steel” (1000 MPa = 1GPa). (World Auto Steel)

Wind and Solar: The main components of a wind turbine are the tower, the nacelle, and the rotor. A foundation connects the turbine to the ground or seabed. All these components depend on steel (World Steel Association, 2012). The nacelle contains key components and some of the highest-value steels. These include electrical steels (also known as lamination, silicon or transformer steels). Electrical steels are a specialty steel tailored to producing the specific magnetic properties that make wind energy possible. The gears of the gearbox were machined using precision tools and special hardened steel components. Most of the steel in a wind turbine is the tower (World Steel Association, 2012).

To construct a tower, fan-shaped plate segments are cut from rectangular parent steel plates and roll-formed and welded into cone sections. A section's thickness may vary from 8 mm at the top to 65 mm at the base, depending on loads and steel grades used. Offshore installations usually use thicker or stronger plates. Longer blades increase the energy yield of a turbine. They sweep a larger area and so capture more wind. The tower and the foundation have to be adjusted to carry these heavier blades and the bigger rotor that they require thereby requiring the demand for high grade steel (World Steel Association, 2012).

Also, to maximise yield, longer blades mean taller towers. Therefore, to carry these longer high grade steel will be required. Higher steel grades can be applied to achieve lighter and taller towers. For example, by upgrading the steel of a wind tower structure from grade S355 to S500 (S = Structural), a weight saving of 30% can be achieved (World Steel Association, 2012).

For PV panels the support structure and panel frames are made of steel (Arcelor Mittal). Options include cold-formed profiles, hollow sections or tubes, coupled with the proper metallic coating (Arcelor Mittal). Optimised steel grades, with excellent corrosion resistance and durability at high temperature are often in PV panels. Stainless steel can also be use in PV panels though conventionally cold formed profiles are used.

Machinery, Metal goods, Tubes and Appliances- In the machinery industry, steels with the higher strength levels available are used in equipment such as cranes, dump trucks and power shovels to reduce weight. The steel plates for construction and industrial machinery, there is a strong need for high strength for weight reduction in the equipment structure. For example, high strength steel plates with 780 MPa in tensile strength are frequently used in parts such as crane booms and outriggers. The requirements placed on these high strength steel plates have diversified in recent years, as exemplified by low temperature toughness to enable use in cold districts and improved weldability by lowering preheating temperature for welding (Hayashi,Koseki,Ogawa, Ikeda and Hatakeyama, 2004)

Metal goods and packaging use steel due to its lasing durability and barrier properties against light, gases and liquids (APEAL, 2015). According to APEAL 67% of packaging steel was recycled in the EU in 2006 and since these goods can use high amounts of recycled steel, it is assumed that about 70% of metal goods comes for recycled steel. The same goes for domestic appliances, since they can be made with stainless steel which is manufactured from scrap in an EAF (Janke, Savov, Weddige, Schulz, 2000).

Tubes are used in steel construction for civil and engineering purposes where the relationship between mass and space occupied is especially critical. Therefore, High strength seamless steel tubes will be required to maximize efficiency as they are characterized by elevated yield strength and very good toughness at low temperature, with a chemical composition that guarantees an optimum weldability (Tenaris, 2014).

Therefore, from the different types of steel demanded by the end use sectors and the types of steel produced from the EAF route (stainless steel, construction steel) as stated earlier in this subchapter, it can be concluded that construction steel with tensile strength < 500 MPa and stainless steel products that can be met mostly with scrap will be part of low grade steel. Therefore, as stated in the methodology chapter, steel for these end use sectors can be produced using an EAF with 100% scrap feed.

Steel that require high strength, low weight, high stress resistant and high tensile strength of maximum 1400 MPa will be called high grade steel.

For the “other” sector which includes other miscellaneous products and power production technologies as detailed in the end use sector subchapter of the results chapter, the current share of BOF and EAF facilities in the EU will be used to divide the steel demand in this sector into high and low grade. This helps for the analysis of preferred production route as it was stated in the methodology chapter that the grade of steel division will depend on the ability of the production route to meet that grade. The current share of BF- BOF and EAF in the EU is 57% and 43% respectively (EUROFER, 2016)

Figure (27 and 28) shows the steel demand of the end use sectors based on grade from 2016 to 2050.

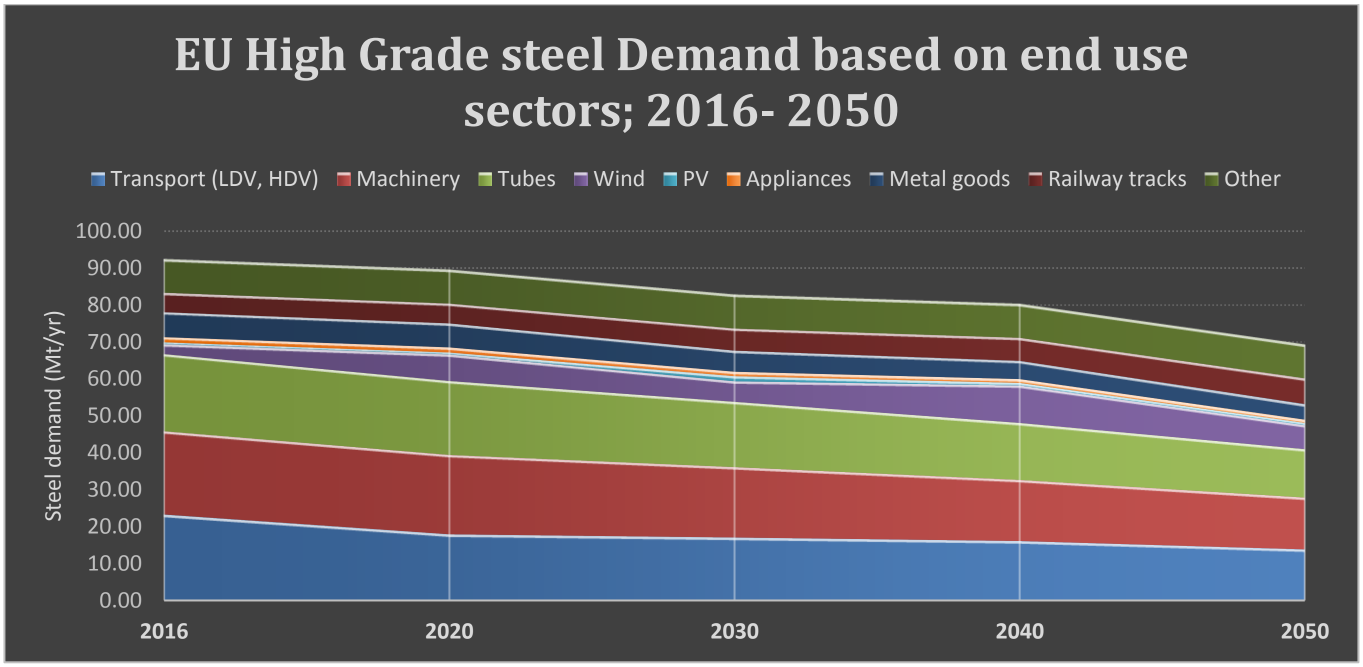


Figure 27: End use sector share of high grade steel demand

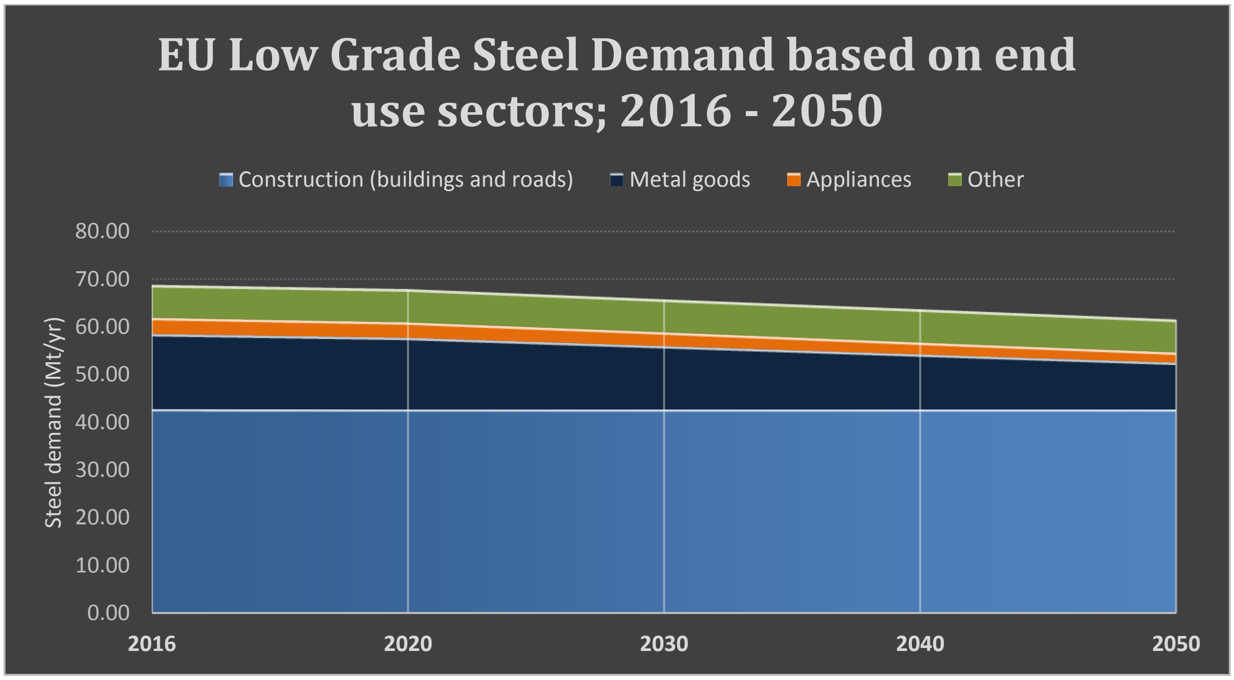


Figure 28: End use sector share of low grade steel demand

Table (9) provides the % share of end use sector high grade steel demand

Table 9; Share of end use sector high grade steel demand

	2016	2020	2030	2040	2050
Transport (LDV, HDV)	25%	20%	21%	20%	20%
Machinery	24%	24%	23%	21%	20%
Tubes	23%	22%	21%	19%	19%
Wind	3%	8%	7%	13%	9%
PV	1%	1%	2%	1%	1%
Appliances	2%	2%	1%	1%	1%
Metal goods	7%	7%	7%	6%	6%
Railway tracks	6%	6%	7%	8%	10%
Other	10%	10%	11%	11%	13%

High grade steel demand declines from 92 Mt in 2016 to 69 Mt in 2050. Machinery, transport and tubes together account for 60% share of high grade steel demand. Renewables like wind and PV make up 10 % with wind having a major share due tohigher capacity addition and greater amount of steel required than PV. 70% of appliances and metal goods are made of scrap, therefore a small share of these sectors will require primary iron and can be attributed to be produced from a blast furnace which is used to make higher grade steel as mentioned in the methodology chapter.

Table (10) provides the % share of end use sector low grade steel demand.

Table 10: % share of end use sector low grade steel demand

	2016	2020	2030	2040	2050
Construction (buildings and roads)	62%	63%	65%	67%	69%
Metal goods	23%	22%	20%	18%	16%
Appliances	5%	5%	4%	4%	3%
Other	10%	10%	10%	11%	11%

Low grade steel demand declines from 69 Mt in 2016 to 61.5 Mt in 2050. In 2050 construction accounts for 69 % of the steel demand for low grade while metal goods and appliances account for 16% and 3% respectively. Steel demand for construction (buildings and roads) remains nearly constant at 42 Mt/yr. Therefore, increased share for construction from 62% in 2016 to 69% in 2050 is due to the decline in demand for metal goods and appliances.

The EU scrap supply from 2020 to 2050 increases from 100 Mt to 135 Mt (Pauliuk, 2013). Figure (29) shows the projected EU scrap supply till 2050

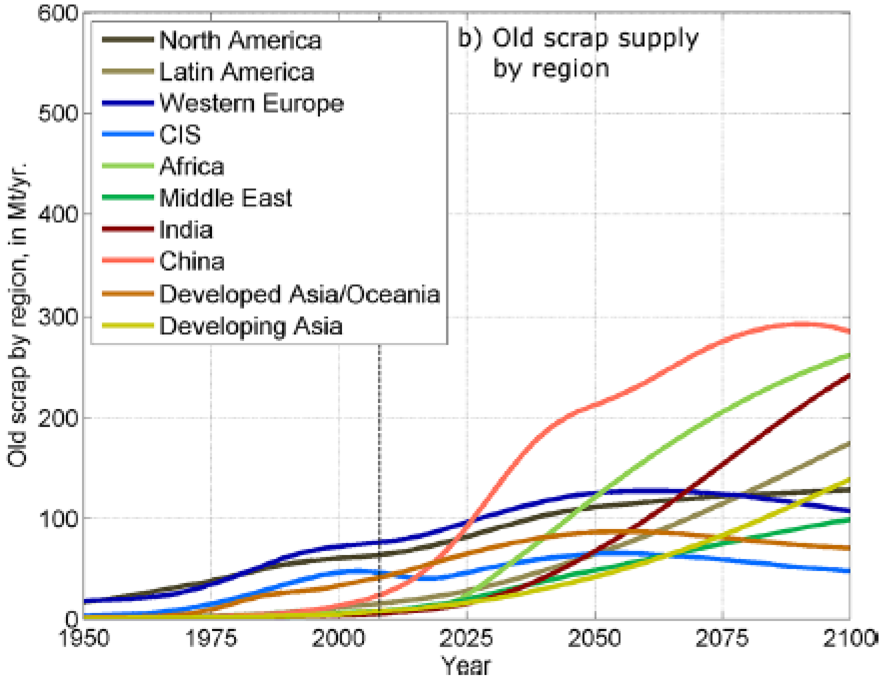


Figure 29: Projected regional scrap supply (Pauliuk, 2013)

Using the scrap supply projected in Figure (29) and the share of high and low grade steel demand, Figure (30) is modeled to show the scrap supply and share of high and low grade steel demand from 2020 till 2050 to see if scrap supply can meet future steel demand (2020 – 2050).

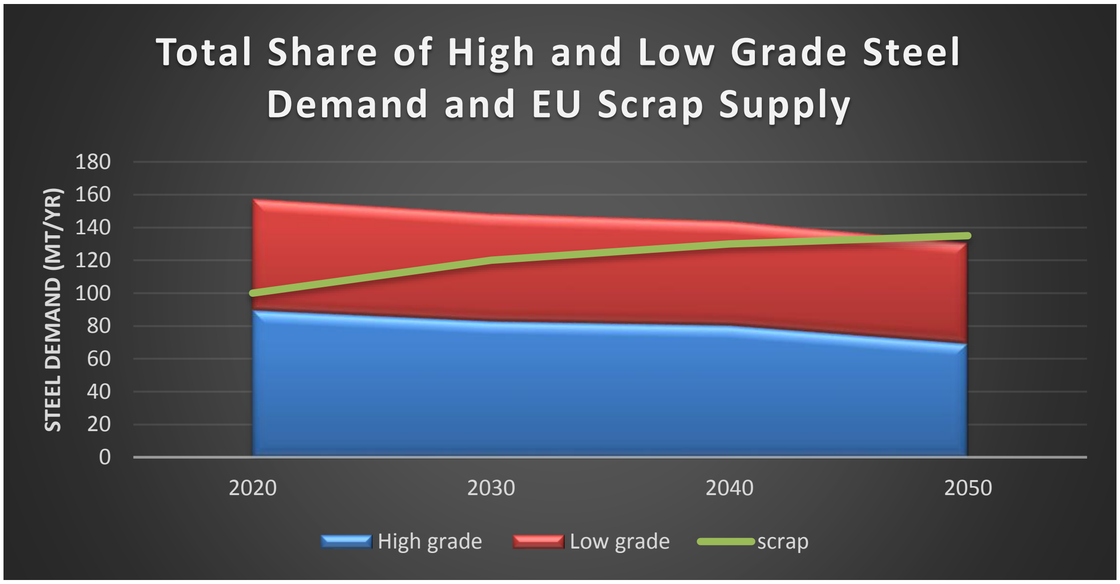


Figure 30: Total share of high and low grade steel demand and EU scrap supply, 2020-2050

The share of high grade steel declines from 57% in 2016 to 53% in 2050 while the share of low grade steel increases from 43% in 2016 to 47 % in 2050. This increased share of low grade steel is due to the nearly constant demand for construction and engineering steel for building while the steel required for other end use sectors requiring high grade steel declines due to lower demand of product for that sector (Machinery, tubes) and weight reduction potentials thereby using less steel.

Figure (30) shows that the EU scrap supply exceeds demand by 2050. At first glance this mean that EU scrap supply can meet EU steel demand in 2050 but as mentioned earlier in this report, scrap contains impurities and residual elements and therefore cannot meet the constraints set for high grade steel (Janke, Savov, Weddige, Schulz, 2000). Therefore, there will still be a need for primary iron to meet future steel demand in the EU.

Production Pathway.

Figure (30) showed that there is still a requirement of primary iron to meet high grade steel demand since it will account for 53% of steel demand in 2050. Therefore, there is a need for a blast furnace – basic oxygen furnace since it uses primary iron as input (IEA, 2009, 2010). The share of low grade steel demand is 47 % in 2050. Therefore, the need for an EAF to meet low grade steel demand is also required. So, an integrated production route is proposed which includes a BF-BOF for production of high grade steel and an EAF for the production of low grade steel. The current best available technology uses 25 % scrap feed in a blast furnace and 100 % scrap in an EAF (IEA, 2010).

Table (11) shows the calculations for scrap and primary iron required to meet the EU steel demand using the integrated production route

	2020	2030	2040	2050
High grade; BF –BOF (Mt/yr)	89.56	82.80	80.28	69.28
low grade EAF(Mt/yr)	67.87	65.66	63.48	61.33
TOTAL (Mt/yr)	157.43	148.46	143.76	130.61
Scrap EU (Mt/yr)	100	120	130	135
Scrap needed for BF-BOF (25%) (Mt/yr)	22.39	20.70	20.07	17.32
Scrap fed into EAF (100%) (Mt/yr)	67.87	65.66	63.48	61.33
Scrap remaining after BOF and EAF (Mt/yr)	9.74	33.64	46.45	56.35
Primary Iron required (Mt/yr)	67.17	62.10	60.21	51.96

Table 11: Calculations for steel, scrap and primary iron required for integrated route

Figure (31) sow the graphical representation of share of steel produced from BF-BOF and EAF, and figure (32) shows the share of scrap that is fed into the BF-BOF and EAF, share of excess scrap and primary iron required to meet steel demand.

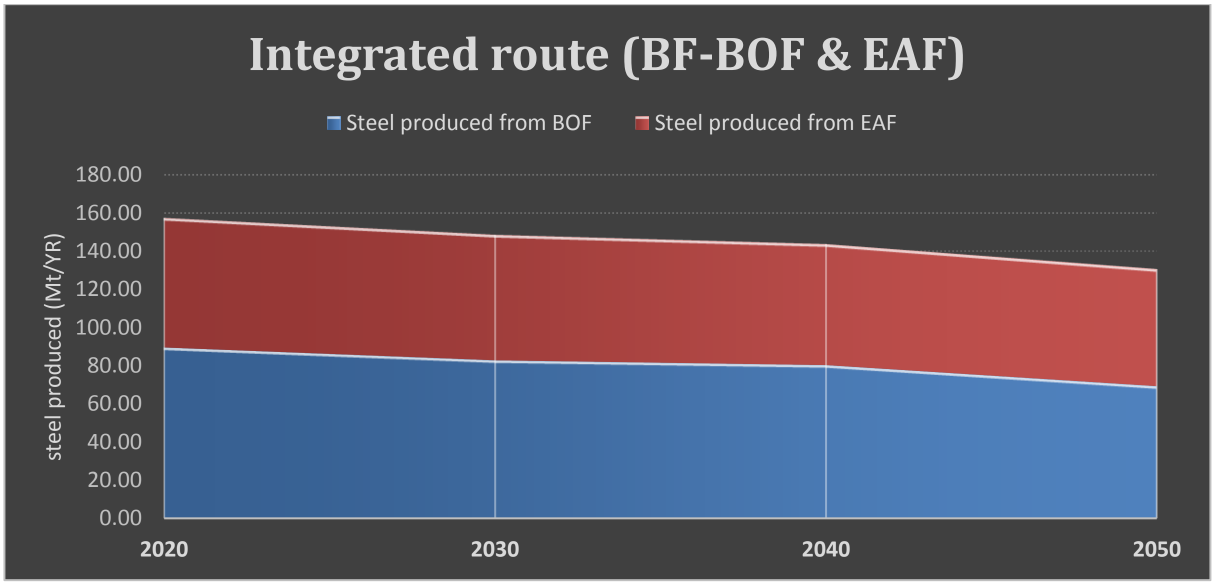


Figure 31: Projected share of BF-BOF and EAF production routes

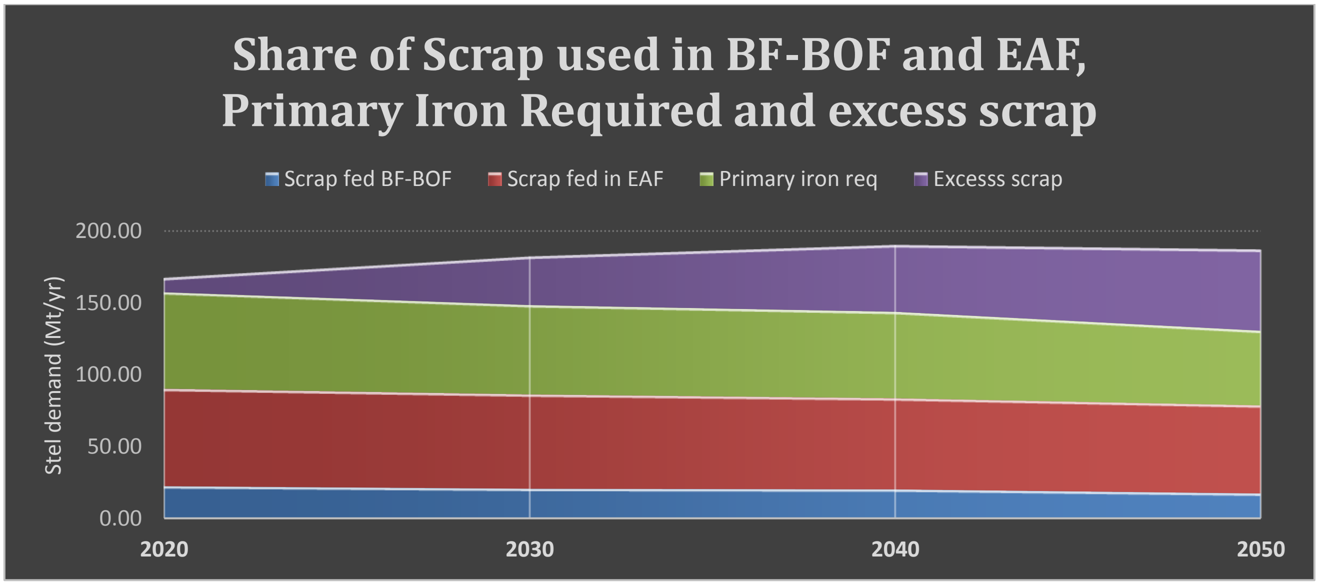


Figure 32: Share of scrap fed into BF-BOF and EAF and primary iron required for the integrated route

Share of steel produced from the BF-BOF route and the EAF route follows the share for high and low grade steel demand (53% BF-BOF, 47% EAF). Using a 25 % scrap feed for the BF-BOF the scrap demand for this route will decline from 22 Mt in 2020 to 17 Mt in 2050 due to the decrease in demand for high grade steel. The amount of primary iron required to meet this demand declines from 67 Mt in 2020 to 51 Mt in 2050. The EU scrap supply is sufficient to meet all the low-grade steel demand from 2020 to 2050 since scrap supply is substantially higher than low grade demand. With increasing scrap supply and low demand for low grade steel, excess scrap will remain (9.7 Mt in 2020 and 56 Mt in 2050)

CO2 Emissions

Figure (33) Shows the emissions form a typical steel mill.

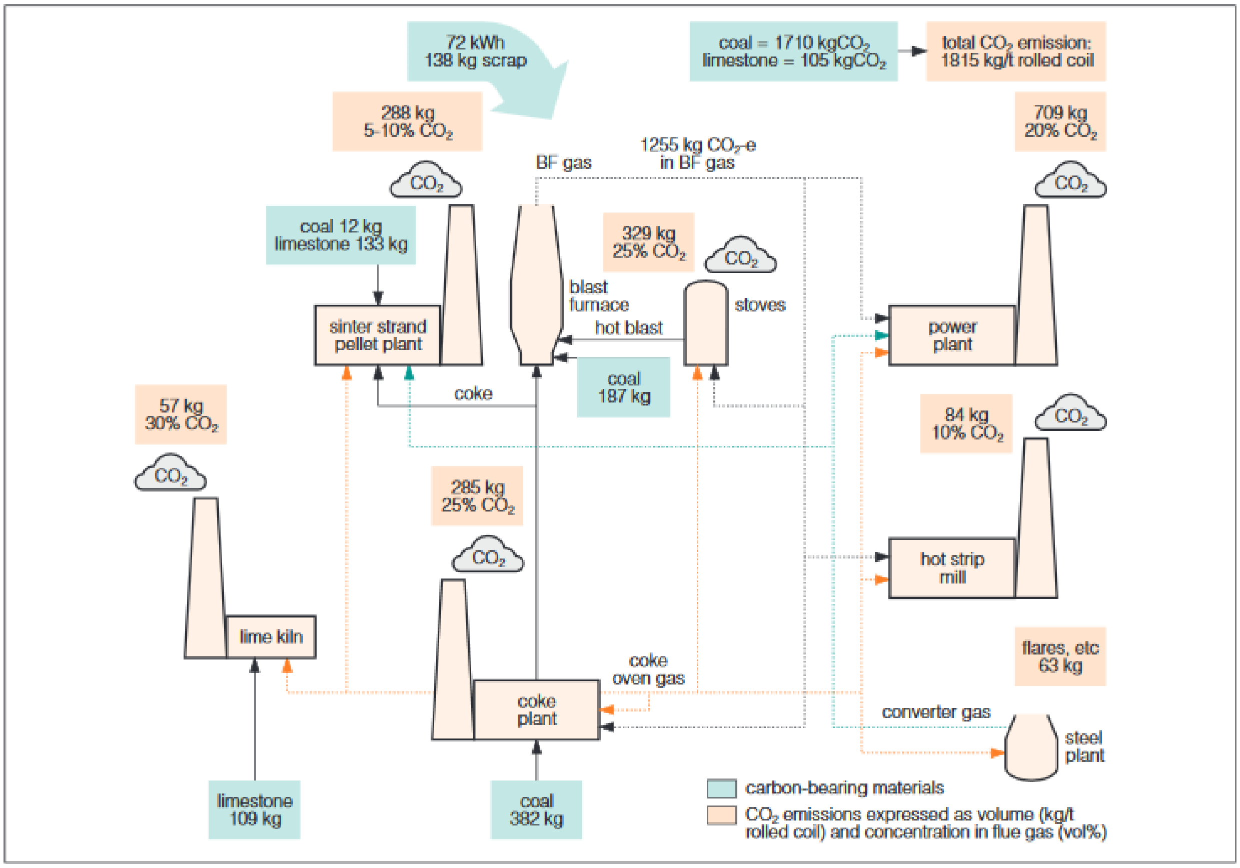


Figure 33: CO2 emissions sources in a steel mill Source: IEA (2012)

CO_2 emissions for the BF BOF route can emit between 1.6 TO 1.9 tCo_2/t crude steel due to the use of coke, coal and fossil fuels to heat the iron ore. While CO_2 emissions for the EAF route depend on the electricity mix of the region where the facility is built. Therefore, CO_2 emissions for the EAF route vary from 0.6 to 0.9 tCO_2/t crude steel since it uses electricity and no direct fossil fuel use (IEA, 2012).

Figure (34) shows the CO_2 emissions for the two production routes to meet future EU steel demand.

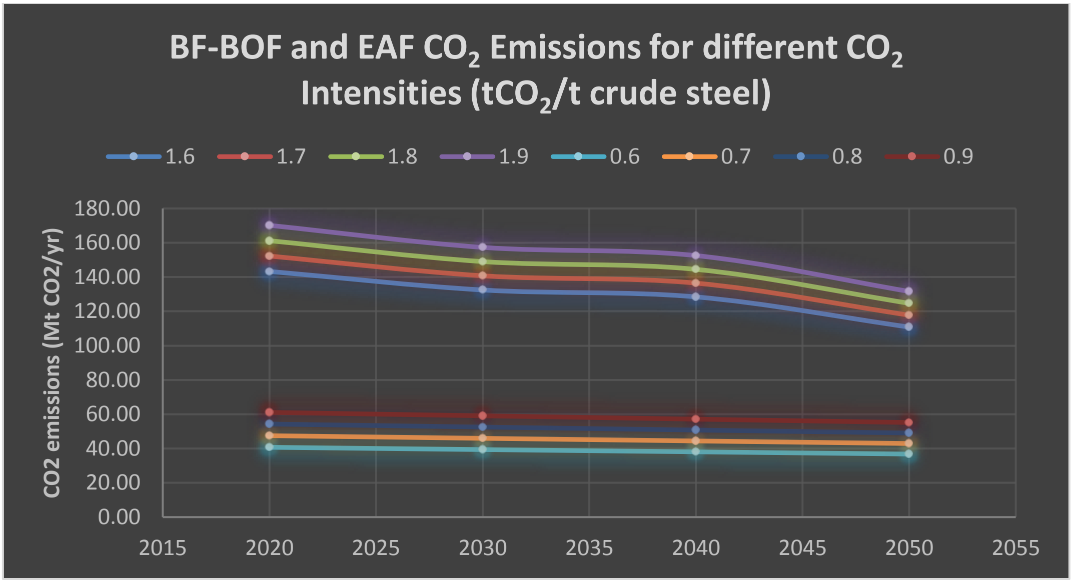


Figure 34: BF-BOF and EAF CO2 emissions for different intensities

In 2020 based on the steel demand projections calculated in the results chapter, the CO_2 emissions from the BF-BOF production route range from 143Mt CO_2 for a CO_2 intensity of 1.6 tCO_2/t crude steel to 170 Mt CO_2 for a CO_2intensity of 1.9 tCO_2 /t crude steel. In 2050 the emissions from the BF-BOF production route range from 110 Mt CO_2 for a CO_2 intensity of 1.6 tCO_2/t crude steel to 131Mt CO_2 for a CO_2intensity of 1.9 t CO_2 /t crude steel. The decline in CO_2 emissions can be attributed to the decline in steel demand in the EU.

For the EAF route the CO_2 emissions from steel production ranges from 40Mt CO_2 for a CO_2 intensity of 0.6 tCO_2/t crude steel to 61 Mt CO_2 for a CO_2intensity of 1.9 t CO_2 /t crude steel in 2020. In 2050 the emissions range from 36 Mt CO_2 for a CO_2 intensity of 0.6 tCO_2/t crude steel to 55Mt CO_2 for a CO_2 intensity of 0.9 t CO_2 /t crude steel. The emission decline rate for the EAF route is lower than the decline rate of the BOF route due to the assumption of constant addition of building stock for the construction sector in the methodology chapter.

Since an integrated route is proposed in this report, the emissions of the combined routes are presented in figure (35)

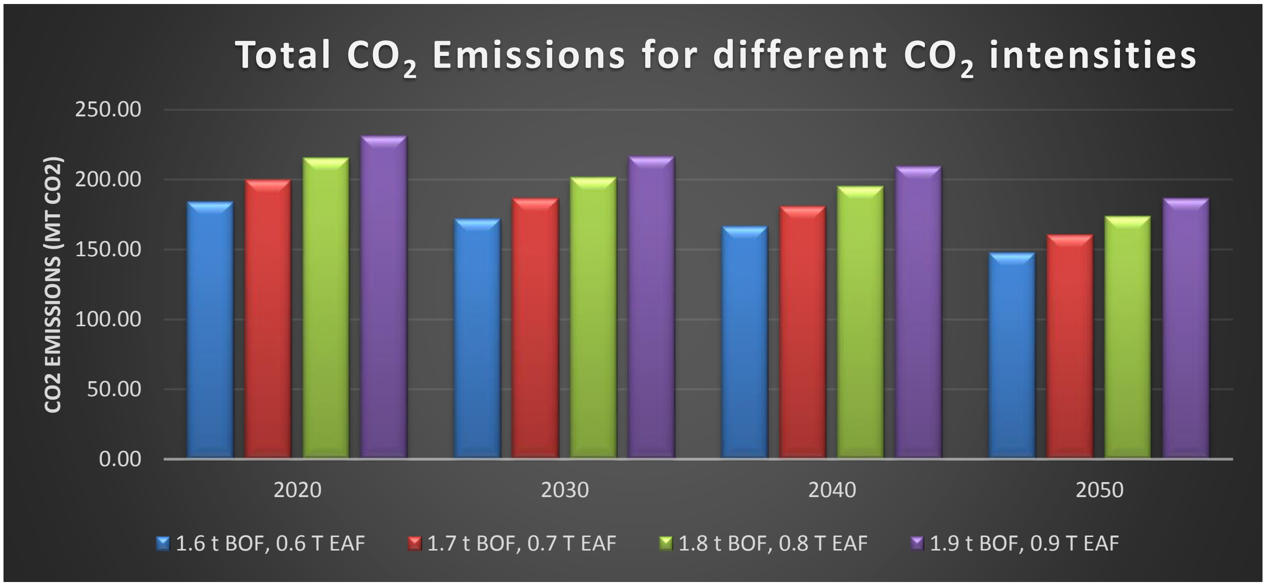


Figure 35: Total CO2 emissions for the integrated route

For the integrated route the CO_2 emissions range from 184 $MtCO_2$ [CO_2 intensity of 1.6 tCO_2/t crude steel (BF- BOF),0.6 tCO_2/t crude steel (EAF)] to 231 Mt CO_2 [CO_2 intensity of 1.9 tCO_2/t crude steel (BF- BOF),0.9 tCO_2/t crude steel (EAF)] in 2020.

In 2050 these emissions decline to 147 Mt CO_2 [CO_2 intensity of 1.6 tCO_2/t crude steel (BF-BOF),0.6 tCO_2/t crude steel (EAF)] and 186 Mt CO_2 [CO_2 intensity of 1.9 tCO_2/t crude steel (BF-BOF),0.9 tCO_2/t crude steel (EAF)] This decline in CO_2 emissions correlates with the decline in steel demand with the BF-BOF production route contributing around 70% of the total emissions for the integrated route.

Discussion (Sensitivity Analysis)

Sensitivity analysis was performed on the LDV (transport) and construction sector since they contribute to about 60 % of the total steel demand. Sensitivity analysis was already performed on the CO_2 emissions for the integrated route in the CO_2 emission subchapter.

For transport a high demand scenario **R5** from the SULTAN scenario tool was used to see the change in steel demand if LDV ownership increases. The purpose of this scenario was to explore what the potential impact might be of lower levels of future transport activity/demand. Like scenario **R2**, this scenario is based on core **R1** scenario but with higher rates of demand/activity increase to and additional/strengthened policy actions to bring total GHG emissions back to the 2050 target levels;

Figure (36) shows the LDV sales for the high demand scenario

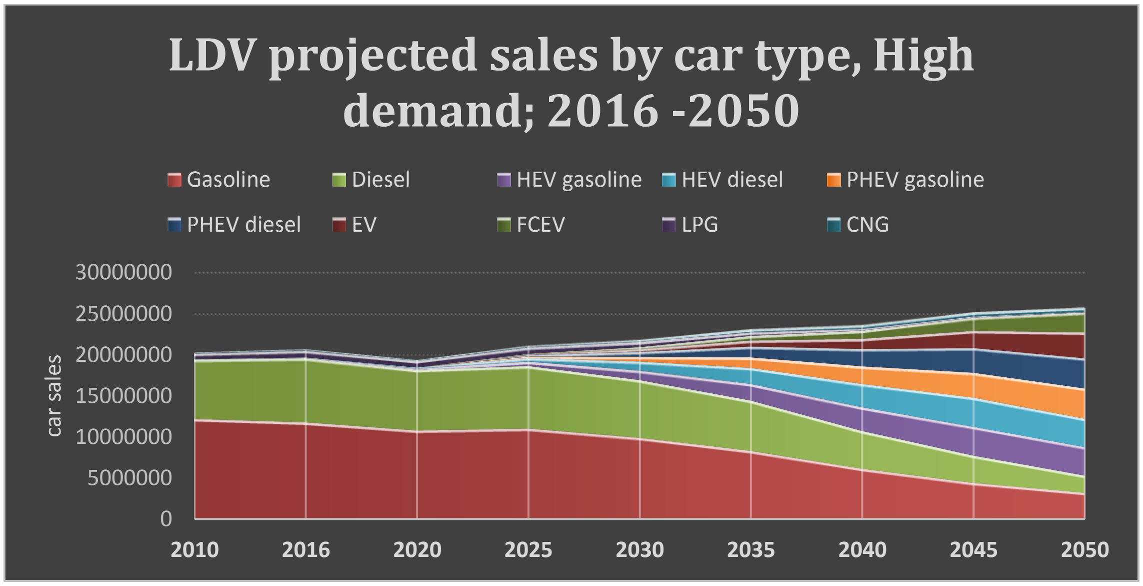


Figure 36: LDV sales projection in the EU (R5 scenario)

LDV sales increase from 20 million in the **R2** scenario to 25 million in the **R5** scenario in 2050. In the high demand scenario, the share of different types of LDV's in 2050 is nearly equal due to the scenarios assumption of lower activity in type of car sale. The steel demand in the high demand scenario is provided in figure (37).

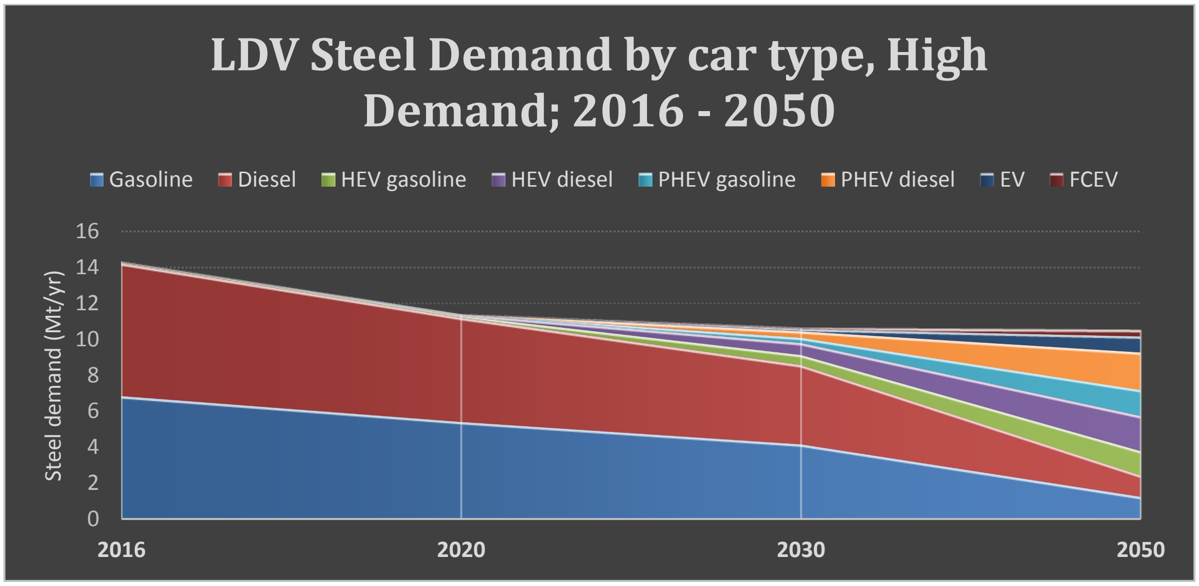


Figure 37: Projected EU steel demand for LDV's based on the R5 scenario

Steel demand increases from 8.9 Mt in the **R2** (low biofuel GHG savings) scenario to 10.5 Mt in the R5 (high demand) scenario. This increase in steel demand can be attributed to the increased sales of cars and the increased share of gasoline and diesel vehicles in 2050 as compared to the R2 scenario. This increase of 1.5 Mt is minimal and thus, has a negligible effect on the share of high and low grade steel demand.

For the construction sector, sensitivity analysis was performed on the building sector since it accounts for a major share of yearly steel demand. The building stock intensity per capita was used project the total building stock expected in 2050. And compare it to the projections 240 million residential stock proposed by the IEA Blue Map scenario. The 2005 total residential building stock in the EU was 200 Million (IEA, 2009). With non-residential stock accounting for 25% of the total building stock, the total building stock in 2005 amounts to 267 Million. Using the same methodology in the end use sector results chapter the yearly added building stock and yearly steel demand for buildings is calculated. Table (12) provides the results of the calculation

	2050
Total stock (residential +non residential)	292 Million
Yearly added stock	3.9 Million
M^2/dwelling	80 (residential); 450 (79%), 900 (21%) (non-residential)
T steel/m^2	0.04
Yearly steel demand for new built	30.5 Mt
Yearly steel demand (new built +refurbishments)	38.2 Mt

Table 12: yearly steel demand for buildings based on population growth

The building stock when correlated with population growth, projects a lower total building stock in 2050 than the projections made in the BLUE Map scenario. This difference can be due to the assumption made in the BLUE Map scenario that in order to meet the BLUE Map emission goals of 2050 new and existing buildings will need to have higher standards. Therefore, some current buildings that do not meet the standards set for buildings to meet CO_2 goals by 2050 will need to be demolished and replaced or renovated with new building standards.

Table (12) shows that the yearly added building stock is 3.9 Million as compared to 4.2 Million calculated in the results chapter. This translates to a yearly steel demand of 38.2 Mt. this demand is 3 Mt less than the demand calculated in the results chapter. Therefore, using the building stock intensity per capita to project stock demand till 2050 instead of the BLUE Map projected stock has minimal effect on the on the share of high and low grade steel.

For the machinery, appliance, metal goods and tubes sectors, an average yearly decline rate chosen to extrapolate till 2050 the steel demand for these sectors. This method does not account for events that would increase or further decrease the steel demand for these sectors.

In the report, end use sectors such as conventional power plants, and other modes of transport such as ships were not investigated and therefore were categorized as “Other” sector in the results chapter. Steel demand for the other sector was taken to be constant till 2050 and therefore does not account for an increase or decline in steel demand, especially for the conventional power plants as according to the IEA Blue Map scenario renewables are expected to have a 50 % share in power generation by 2050.

Recommendations

The BF-BOF process emits more CO_2 (1.6.-1.9 tCO_2/t crude steel) than the EAF process (0.6-0.9 tCO_2/t crude steel) and has a higher share of the steel demand. Therefore, technologies to reduce CO_2 emissions from the BF-BOF process is paramount to meet the BLUE Map scenario targets for 2050.

ULCOS is a large European research project that aims to identify and develop technology that could enable a drastic reduction in CO_2 emissions from ore-based steel production. The Iron making flowsheeting model (IRMA) has made a vital contribution to one of the ULCOS subprojects, as IRMA models were used to evaluate the economics and CO_2 reduction potential of a large number of alternative ironmaking routes. IRMA is a software tool that allows for the use of thermodynamic data relevant to iron- and steelmaking in a flowsheeting environment. (revue de metallurgy, 2009)

The ULCOS technologies assessed can be divided into two categories:

1) The advanced existing route that are incremental improvements of existing technologies
    a. The advanced blast furnace with oxygen injection and CCS
2) Breakthrough technologies which are not supposed to be implepented before 2025- 2030
    a. Smelting reduction process with CCS.

The extensive use of BATs could result in energy and CO2 reductions of around 20%. This reduction potential will not be enough to meet the BLUE Map scenario goals of reducing CO_2 emissions (IEA, 2010). A net reduction in energy demand and emissions will, therefore, be dependent on significant innovation strategies bringing new technological solutions on stream well before 2050.

Figure (38) represents the projected direct emission reduction by technology option for the iron and steel industry as proposed in the BLUE Map scenario.

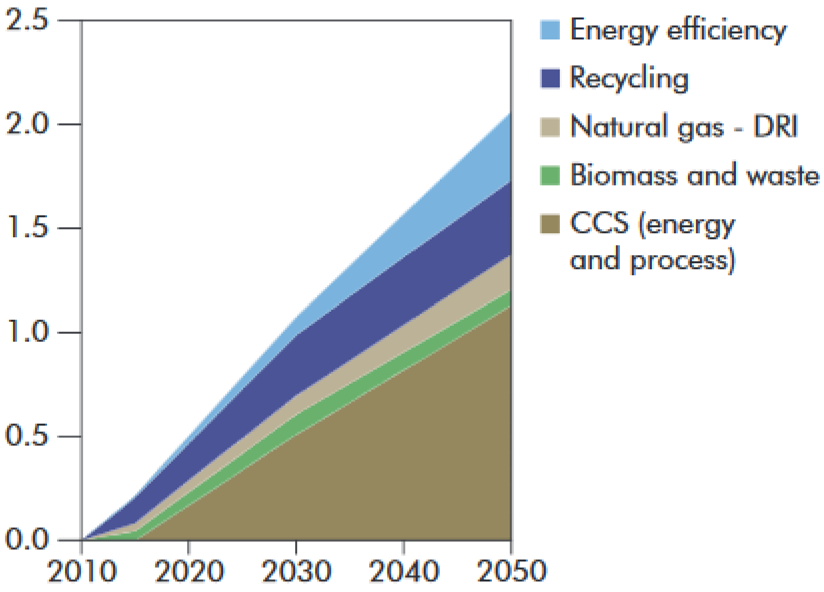


Figure 38: Direct emission reduction potential of various technologies.

Source IEA (2010)

The figure shows that about 55% of the emission reduction in 2050 can be attributed to CCS with CCS technologies being introduced on a commercial scale post 2020 (IEA, 2010). Therefore, combining CCS with the ULCOS technologies stated earlier, will provide a high emission reduction potential.

Oxyfuelling to generate pure CO2 off gas.

Blast furnaces emit between 1.5 to 2.0 tCO_2/t of iron produced. Redesigning the blast furnace to use oxygen helps remove CO_2 from the flue gas. With oxygen injection into the blast furnace and coupled with CCS, 80% reduction in CO_2 emissions can be achieved (IEA, 2009).

Figure (39) shows the CO_2 emissions reduction for the integrated route using the oxyfuelling technique along with CCS.

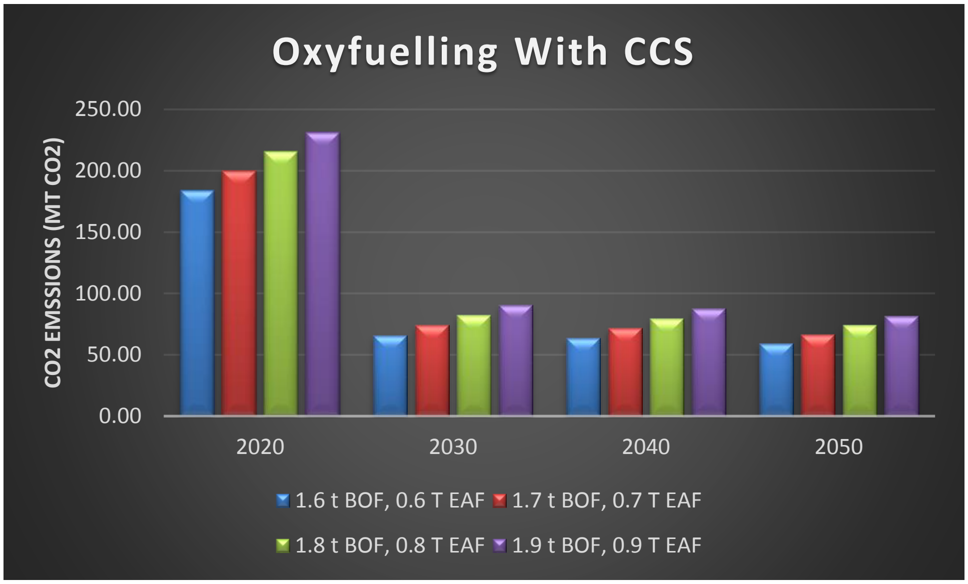
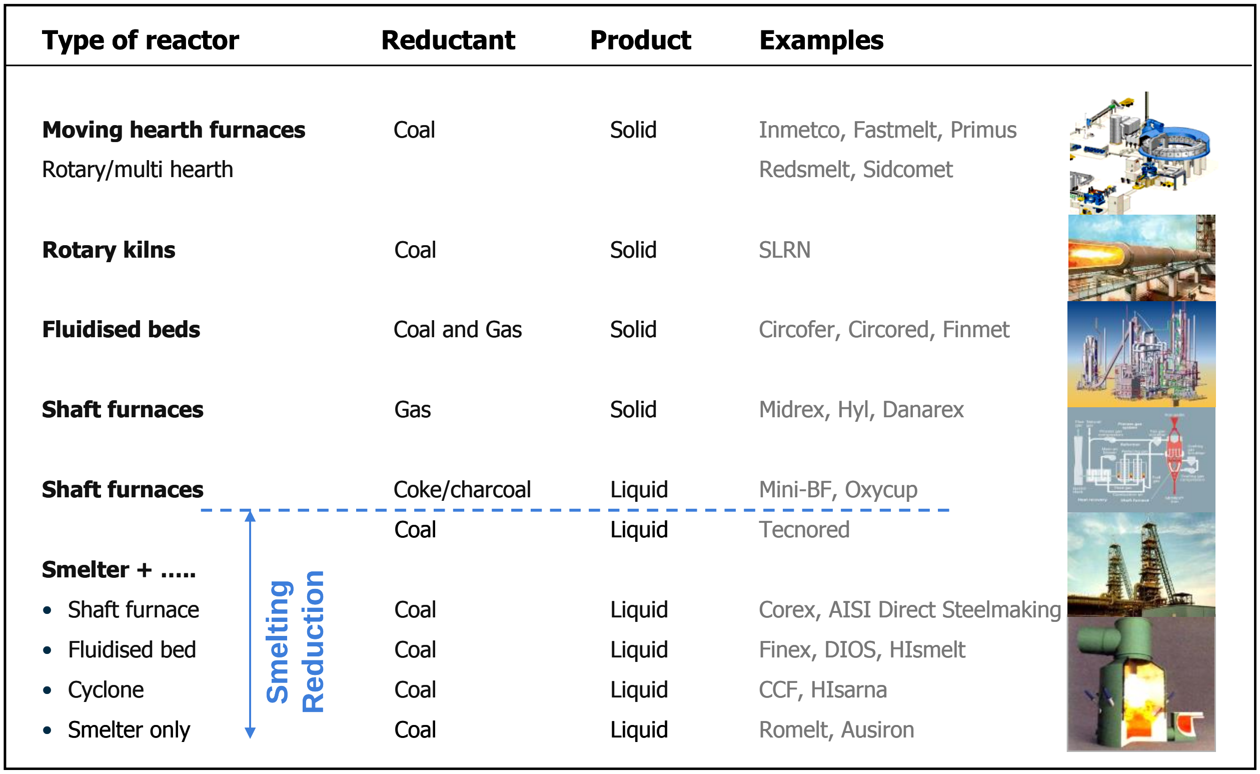


Figure 39: Integrated route CO_2 emissions using oxyfuelling with CCS

Though Oxyfuelling currently exists, cost effective and efficient CCS technologies will only be available post 2020 (IEA, 2010; Imperial College London, 2012) therefore the reduction in emissions is only calculated for the year 2030 and onwards. This provides an emission reduction of 55% when compared to figure (35) which is in line with the BLUE Map projections.

Smelting Reduction

Figure (40) shows the different alternate ironmaking process



Type of reactor	Reductant	Product	Examples
Moving hearth furnaces Rotary/multi hearth	Coal	Solid	Inmetco, Fastmelt, Primus Redsmelt, Sidcomet
Rotary kilns	Coal	Solid	SLRN
Fluidised beds	Coal and Gas	Solid	Circofer, Circored, Finmet
Shaft furnaces	Gas	Solid	Midrex, Hyl, Danarex
Shaft furnaces	Coke/charcoal	Liquid	Mini-BF, Oxycup
	Coal	Liquid	Tecnored
Smelter + ...			
• Shaft furnace	Coal	Liquid	Corex, AISI Direct Steelmaking
• Fluidised bed	Coal	Liquid	Finex, DIOS, HIsmelt
• Cyclone	Coal	Liquid	CCF, HIsarna
• Smelter only	Coal	Liquid	Romelt, Ausiron

Figure 40: Alternate iron making processes

Source: Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel

The smelting process uses coal as reductant, not coke or gas. From table 1 the following processes can be considered Smelting Reduction processes; *Corex, Finex Tecnored, AISI Direct Steelmaking, DIOS, Romelt, Ausiron, HIsmelt, CCF and HIsarna* (Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel)

The reason to investigate the smelting process is it uses coal instead of coke and coke is the biggest threat due to the need for high quality coking coal and because of the environmental issues of coke making (Chatterjee, 1992). The different smelting processes are described below:

Corex

The process combines pre-reduction of ore in a shaft furnace, to a level of about 80 %, with final reduction and melting in a melter/gasifier. The reduction shaft requires lumpy or agglomerated iron ores. The fuel rate is high and so is the amount of export energy in the form of combustible gas. The process is not completely independent of coking coals. Corex requires 200 kg/thm of coke. Adding more coke improves the productivity. Another drawback of the Corex process is that it depends on efficient usage of the large amount of export gas for its economic viability (Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel).

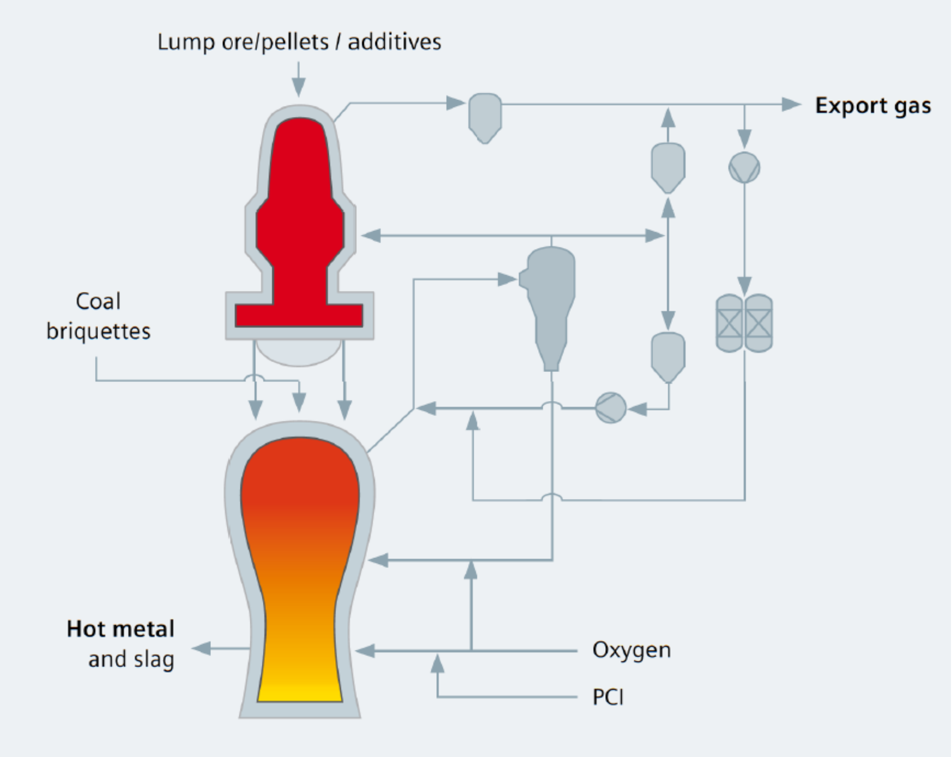


Figure 41: COREX process

Source: Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel

Finex

In the Finex process the reduction shaft of the Corex is replaced by a series of fluidized beds. This enables the Finex process to use fine ores instead of lump ore or pellets. As a result, the process requires neither coke making nor ore agglomeration. Briquetting of the pre-reduced ore and the coal, pulverized coal injection and controlled charging of the melter/gasifier have improved the fuel rate of the process compared to the original Corex process. The process includes a CO_2 scrubber. The isolated CO_2 can be stored geologically if such a storage is available (Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel)

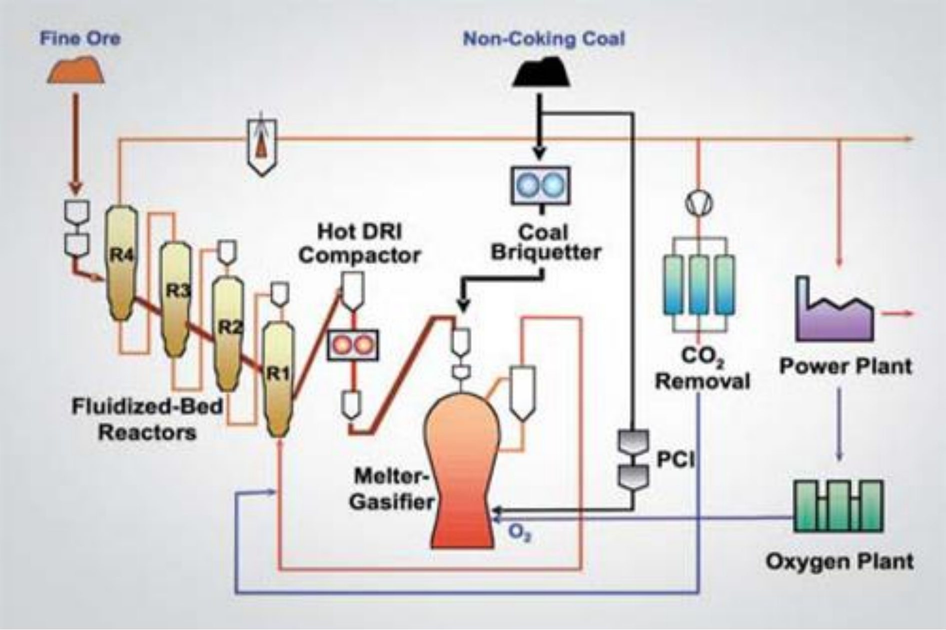


Figure 42: FINEX process

Source: Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel

Tecnored.

The Tecnored process is developed in Brazil. The process uses self-reducing briquettes from iron ore and fine coal. These briquettes are cold bonded. Iron ore reduction in the self-reducing briquettes is very fast and the process doesn't require coking coals. But there are certain quality requirements for the coal. The process prefers lumpy anthracitic coals. The process operates with hot blast of 850°C generated in metallic heaters (Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel)

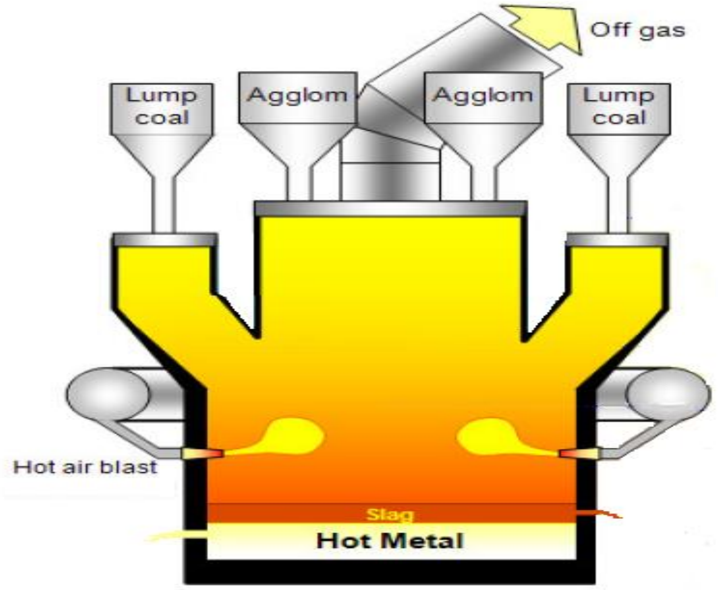


Figure 43: Tecnored process

Source: Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel

HIsmelt

The HIsmelt process combines pre-reduction and preheating of fine ore in a fluidized bed with final reduction in a smelter. The smelter operates with enriched hot blast, generated in blast furnace type stoves. A unique feature of the process is the submerged injection of coal and pre-reduced ore using the so called solid injection lances (SIL). This promotes the transfer of heat from the post combustion zone to the bath. With respect to heat transfer efficiency the process is superior to other smelter processes. The PCR is typically 50 to 60 % (Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel). A drawback of the high PCR is that the pre-reduction of ore in the fluidized bed system is only to magnetite (max. 11 %). With 4 to 5 % FeO in the slag the conditions in the HIsmelt vessel are more oxidizing than in the hearth of a blast furnace. This allows the HIsmelt process to use ores with a higher P content without increasing the P in the metal. The higher FeO content also suppresses Ti reduction allowing the use of high Ti ores without running into slag viscosity problems (Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel).

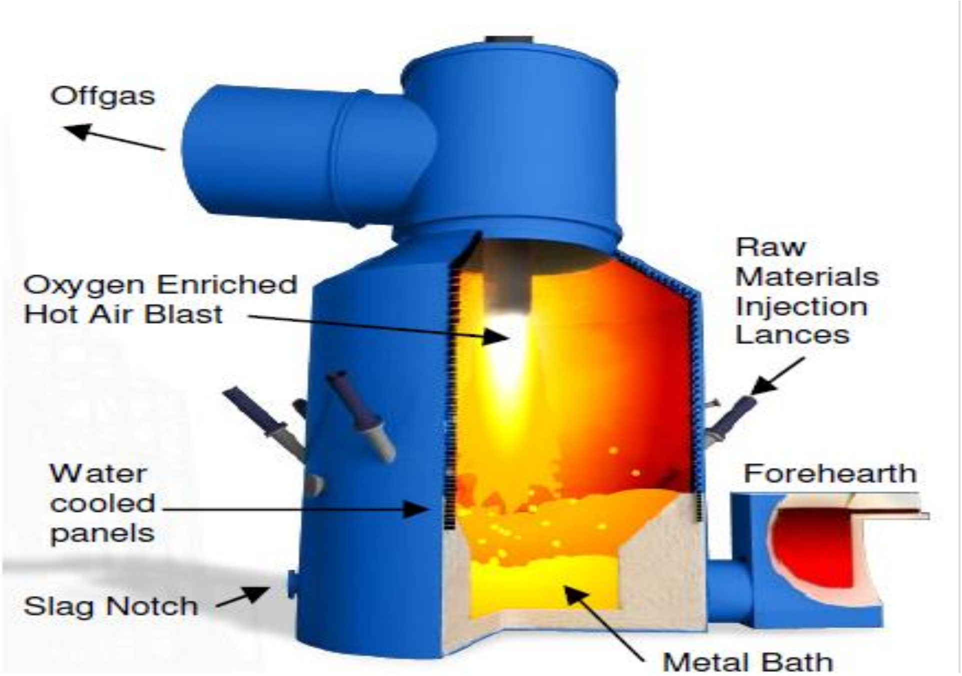


Figure 44: HIsmelt process

Source: Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel

HISARNA

The HIsarna process is a development of the ULCOS project in cooperation with HIsmelt. The HIsarna process can use fine ores and fine coals directly with drying and grinding as the only pre-processing requirements. This means that neither coking nor iron ore agglomeration processes are needed (Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel).

The HIsarna process combines the HIsmelt bath smelting technology with ore smelting and pre-reduction in a cyclone. (Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel).

In contrast to other pre-treatments steps, such as a reduction shaft or fluidized bed, the cyclone is directly connected to the smelter and the smelter gases are neither cooled nor cleaned before they enter the cyclone. It is the only pre-reduction technology that allows integration of both stages into a single reactor vessel. The chemical, as well as the thermal energy of the smelter gas is utilized in the cyclone. Oxygen is injected in the cyclone for the generation of additional heat required for the pre-reduction and the melting of the ore. The cyclone is designed to fully combust the smelter off-gases. The molten, pre-reduced iron ore is transported by gravity as liquid droplets that fall directly into the smelter (Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel). The final reduction and coal gasification stage of the HIsarna process is basically the HIsmelt process with some modifications. In order to make the combination with the cyclone possible the process is operated with pure oxygen instead of enriched hot blast (Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel).

Since the HIsarna process was developed by the ULCOS, where reduction of at least 50 % is envisaged, it is recommended as an alternate option to the oxyfuelling with CCS to meet CO_2 emission goals proposed in the BLUE Map scenario.

The HIsarna process can reduce emissions by 20% but with CCS the reduction potential is 80% (Meijer, Zeilstra, Teerhuis, Ouwehand, van der Stel)

Figure 45 shows the CO2 emissions for the integrated route using the HIsarna process.

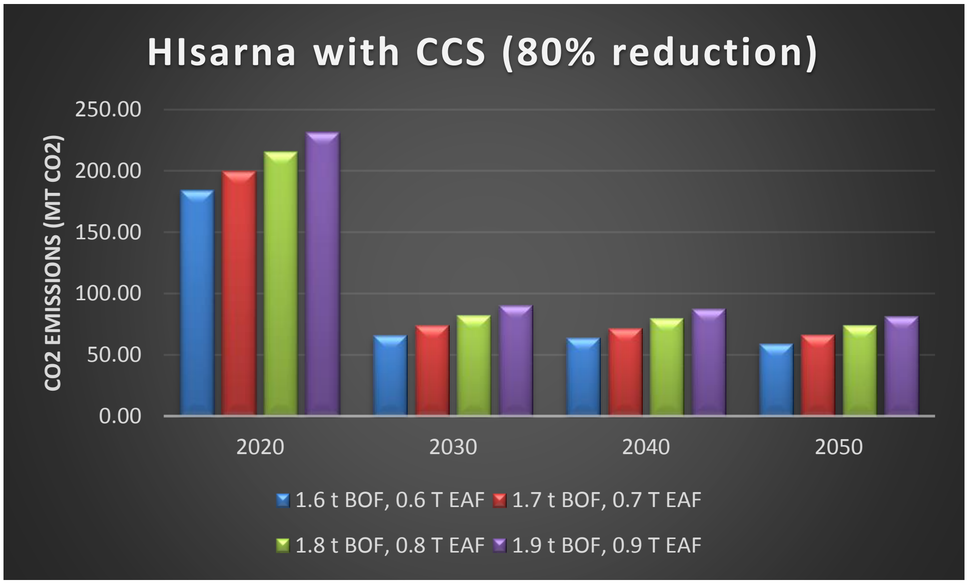


Figure 45; Integrated route using Hisarna process with CCS

The emission reduction was again calculated for the year 2030 and onwards since efficient and cost effective CCS will be deployed by 2030 (IEA, 2010; Imperial College London, 2012).

This provides an emission reduction of 55% when compared to figure (35) which is in line with the BLUE Map projections

Conclusion

This research was performed to project the end use sector steel demand in the EU till 2050 and the share of high and low grade steel to help steel makers decide on a production route. The Steel demand in the EU declines from 161 Mt in 2016 to 130 Mt in 2050 with construction accounting for 38 % of the steel demand in 2050 followed by transport, machinery and tubes which have an equal share of final demand. Decline in steel demand in the transport industry can be attributed to the increased share of EV and FCEV from 2030 and due to LDV weight reduction potential with the use of ultra high strength steel (UHSS). Steel demand for wind peaks at 10 Mt in 2040 due to the increased addition of offshore wind which has a higher steel intensity per MW of installed capacity than onshore wind. The share of high grade steel demand in the EU in 2050 is 53% (transport, railway tracks, wind, solar, machinery, tubes, metal goods, appliances) while the share of low grade is 47 % (construction, metal goods and appliances) with construction accounting for 70% of the low grade demand. Since high and low grade steel have a considerable share of steel demand in 2050, an integrated route using a blast furnace - basic oxygen furnace to produce high grade steel and an electric arc furnace to produce low grade steel is proposed. The EU scrap supply is high and therefore excess scrap will be available even after feeding 25 % scrap into the BF-BOF and 100% scrap into the EAF. Since the share of high grade steel is 53%, primary iron will be required for the BF- BOF to meet high grade steel demand. Using the integrated route produces emissions in the range of 147 Mt CO_2 [CO_2 intensity of 1.6 tCO_2/t crude steel (BF-BOF),0.6 tCO_2/t crude steel (EAF)] to 186 Mt CO_2 [CO_2 intensity of 1.9 tCO_2/t crude steel (BF-BOF),0.9 tCO_2/t crude steel (EAF)]. Using oxyfuelling with CCS or smelt reduction with CCS in the BF-BOF process can reduce emissions from BF-BOF by 80% and 55% from the integrated route.

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Time Planning

Week	Month	Activity
1,2,3 & 4	October	Working on research proposal and meeting with UU and TATA supervisor
6	November	Hand in research proposal
7,8	November	End use sector analysis (wind & PV)
9	December	Meeting with UU and TATA supervisor
10	December	End use sector analysis (transport)
11 & 12	December	Christmas holidays
13,14,15	January	End use sector analysis (transport)
16	January	Meeting with UU and TATA supervisor
17,18,19	February	End use sector analysis (construction)
20,21	February, March	End use sector analysis (Machinery, Tubes and appliances)
22,23	March	Steel grade analysis
23	March	Meeting with UU and TATA supervisor
24	March	Production route decision
25	April	Recommendations for future technologies and Meeting with UU and TATA supervisor
26	April	Hand in final report
27	April	Final presentation