CHALMERS
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Material use in a Low Carbon Energy System

Master's Thesis in Innovative & Sustainable Chemical Engineering and Sustainable Energy Systems

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Department of Space, Earth and Environment
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MASTER'S THESIS 2019

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Report on Material Use in a Low Carbon Energy System
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Cover: Info graphic desgined by freepick

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2019

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Abstract

The European Union has, in line with the Paris Agreement, set out ambitious goals to reduce greenhouse gas emissions by the first half of the century. Achieving these goals will require a massive transformation of the European energy system to a low-carbon based system. The large-scale development of low carbon technologies such as solar, wind, hydro, electric vehicles etc. will have an impact on the demand for energy, material and natural resources. This study analyses the steel demand for wind energy and battery electric vehicles within the European Union until 2050 and explores the CO_2 emissions associated with steel use. Material flow analysis is used to estimate the steel demand which determines the inflow and the outflow of steel in wind turbines and battery electric vehicle fleet considering their end-of-life. The CO_2 emission is quantified based on various scenarios and pathways for the technological development such as HYBRIT (*Hydrogen Breakthrough Iron-making Technology*) along with EAF (*Electric Arc Furnace*) in the European steel industry.

The findings show that the annual steel demands are within the range of 5 – 26 Million tonnes. Estimates of this demand depend on assumptions of parameters, e.g., the penetration level of the low-carbon technologies, average lifetimes, and material efficiency. With this range of steel demand, the steel requirements for BEV production is 17%-87% of the current steel used in the EU automotive sector. Similarly, the steel required for wind energy is about 34%-44% of the current steel consumed in mechanical engineering in the EU. The additional results show that total cumulative CO_2 emissions from steel production for BEV and wind energy would be in the range of 136-382 $MtCO_2$ by 2050 i.e. relatively smaller share (0.004%) of the total EU carbon budget for the period of 2020-2100. The CO_2 emissions associated with the steel produced by HYBRIT and EAF for BEV and wind energy could meet the total target level for the EU steel industry in the European Commission strategic long-term vision for a climate-neutral economy by 2050. However, radial measures have to be taken dedicated for the entire EU steel industry to reduce CO_2 emissions as emissions associated with entire EU steel production would account for 13% of the EU carbon budget in the year 2050.

Keywords: European Union, Battery electric vehicle, Wind energy, Energy systems, Steel, Material flow analysis, HYBRIT, EAF.

Acknowledgements

We would thank our supervisors Johan Rootzén (Division of Energy Technology) and Simon Davidsson Kurland (Physical Resource Theory) for their patience, constant guidance and encouragement through the thesis work. We have been extremely lucky to have had them as our supervisors since they were always available to answer all the questions and queries we had during the thesis work. In particular, we would like to express our sincere gratitude to our Examiner Mikael Odenberger for giving us the opportunity to undertake the thesis and his valuable suggestions.
We are much obliged to the Division of Energy Technology and the people in the division for providing us with useful resources and friendship during our time here. Last but not least our heartiest appreciation to our family and friends, we owe them a great deal.

Krishna K. Kakoti and Worakamon Tasanakul, Gothenburg, June 2019

This thesis is dedicated to the memory of my late father for being my constant source of inspiration and encouragement.

Krishna K. Kakoti, Gothenburg, June 2019

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Abbreviations

BECCS	Bio-energy with carbon capture and storage
BEV	Battery electric vehicle
BF	Blast furnace
BOF	Basic oxygen furnace
CO_2-eq	Carbon dioxide equivalent
DRI	Direct reduction iron
EAF	Electric Arc furnace
ELV	End-of-life vehicle
EOL	End of Life
EU	European Union
GHG	Greenhouse gas
GW	Gigawatt
HYBRIT	Hydrogen Breakthrough Iron making Technology
ICEV	Internal combustion engine vehicle
LCA	Life Cycle Assesment
MFA	Material flow analysis
Mt	Million tonnes
RES	Renewable energy system

1

Introduction

1.1 Background

According to the IPCC, 2018 special report human activities have caused approximately 1.0 °C of global warming above the pre-industrial level, with a range of 0.8 °C to 1.2 °C. Following current trends, the global temperature rise is likely to be 1.5 °C between 2030 to 2052. This has already led to changes in weather and climate extremes and temperature tend to rise. The dependency on fossil energy resources like oil, natural gas and coal, which in most parts of the world has formed the backbone of industrialisation, has also resulted in pollution and environmental damage such as greenhouse gas (GHG) leading to the global warming. In Europe *(EU-28)*, the transport and fuel combustion accounted for nearly 78% of GHG emission in the year 2016 (European Environmental Agency, 2018a). The current transport fleet for passenger vehicles is almost entirely dependent on the petroleum products which has also limited prospects of its short term substitution (Masnadi et al., 2018). Additionally, the electricity generation sector has been taking up a significant share of total CO_2 emissions (Goh, Ang, and Xu, 2018). The International Energy Agency IEA, 2018a reported that CO_2 emissions from coal combustion were contributed to 0.3°C of the 1°C increase in global average annual surface temperatures above pre-industrial levels.

Recognising that climate change represents an urgent threat to societies and the planet, the Paris Agreement was agreed to keep global warming well below 2°C and pursue ambitious efforts to limit the increase to well below 1.5°C (IPCC, 2018). BP Energy Outlook (2019) presents that the rising energy demand at the same time reducing carbon emission is the dual challenge the present economy faces. The emission reduction side will mean shifting towards a low carbon-based energy system as a pathway towards the climate goals outlined in the Paris Agreement. To avoid the negative externalities associated with fossil fuels, a fast transition towards a low carbon energy system based on renewable should be implemented along with the transformation of the energy carrier for the transport sector from a direct fossil fuel combustion to electrification. Technologies such as wind, solar and bio fuels are the basis of a low carbon energy system (Davidsson et al., 2014). This large-scale development of renewable and low carbon technologies will increase the demands on energy as well as material resources (Boubault and Maïzi, 2019).

Moreover, to tackle climate change, enhance energy supply and security and promote sustainability and competitiveness, the European Union has set the creation of a low carbon economy as central policy priority (Simoes, Fortes, Dias, and Seixas, 2015). In 2011, the European Union (EU) reaffirmed its objective to reduce GHG emissions by 80–95% by 2050 compared to 1990 levels. To achieve either of these goals, emissions from the power sector must fall essentially to zero, or even turn negative by 2050 (European Commission, 2016). As per (European Commission, 2018a) the Energy system is responsible for 80% and the power sector contributes to 30% of the total GHG emissions in the EU. Renewable energy sources such as wind, solar, geothermal energy, hydropower, biomass etc will play a vital role in decarbonizing the European energy system (European Commission, 2018a). Similarly, the transport sector is responsible for 27% for the total greenhouse gas emissions in the European Union. According to the European Commission 2018, it aims to reduce 65% of CO_2 emission from passenger car by 2050 (European Commission, 2018a). Thus, increasing penetration of electric vehicles is believed to be beneficial for the mitigation of GHG, emitted by the internal combustion engine, due to zero emission during its use phase (Simon, Ziemann, and Weil, 2015).

Many studies such as (Elshkaki and Graedel, 2013; Kleijn et al, 2011; Davidsson et al, 2014; Jacobson and Delucchi 2011) predict the tremendous growth of renewable energy in the future where Wind energy has a substantial share. Likewise, the (European Commission, 2018a; Simon, Ziemann, and Weil, 2015; Masnadi et al., 2018) also presents prominent shift towards of Electric vehicles in the fleet by 2050. The transformation to implement these low carbon technologies in the energy system as well as the development of Electric Vehicles in the transport fleet, therefore, require energy and material (metals) (Boubault and Maïzi, 2019). Elshkaki and Graedel (2013), refers to these metals as Energy Metals: the bulk of the metals used of energy purposes. But the main concern is if the supply of metals can keep up with demand if these low-carbon technologies are scaled up to substantial levels (Kleijn, 2012). This transformation away from a fossil-based economy is a vital part of sustainable development (European Commission, 2018a)

1.2 Aim and Scope

There is a need to need to study the flow of both bulk and the rare material in the transformation of the energy system. The aim of this study is to project steel required in the increasing battery electric vehicle (BEV) and wind energy to build turbines, until 2050 in a focused system boundary of European Union steel industry regarding persuasion of decarbonization energy systems. Apart from the estimation of materials used in the BEV and wind turbine, the CO_2 emission corresponding to the material consumed by these two low-carbon technologies will also be investigated. Furthermore, different pathways for steel production will be developed in order to explore the steelmaking technology mix that can reduce greenhouse gas emission from steel production. The study is based on scenarios developed by the (European Commission, 2018a) on the share of wind power and the battery electric vehicles in the economy until 2050. The processes considered in this study consist of material production (both primary and secondary production from the recycling of metals) for low-carbon technology and end of life (EOL). The lifetime of the BEV and wind power will also be included in this analysis to investigate the additional material required for building new products. The main overarching Research question of the study is:

> *"How does the upcoming transition of the European energy system affect the requirement of steel used for BEV and Wind Energy and the GHG emissions associated with its production?"*

The study will answer the following sub-questions derived from the main overarching research question:

1. What are the steel requirement for Wind Energy and BEV, based on their projected capacity increase by 2050?
2. What are the CO_2 emissions associated with the steel production for wind energy and BEV?

3. How do the pathways based on the different share of steelmaking technologies reduce CO_2 emission from the current steel production for BEV, wind energy and the entire EU steel production?

The project will provide inputs to the *"The Mistra Carbon Exit"* research program, which has the aim to analyse and demonstrate how the supply chains of buildings, infrastructure and transportation can be transformed to comply with the Swedish target of net zero Greenhouse Gas (GHG) emissions by the year 2045 (Mistra Carbon Exit, 2018).

2

Theory

The European Union's total GHG emission in 2016 was 4441 megatonnes (Mt) carbon dioxide equivalent (CO$_2$eq) that is 22% less than 1990 levels. The EU still remains on track to achieve a 20% decrease in GHG emissions by 2020 compared to 1990 levels, despite emission increasing by 0.6% from 2016 to 2017. The projections depict the reduction of EU's GHG emission until 2035, as shown in Figure: 1. (European Environmental Agency, 2018b).

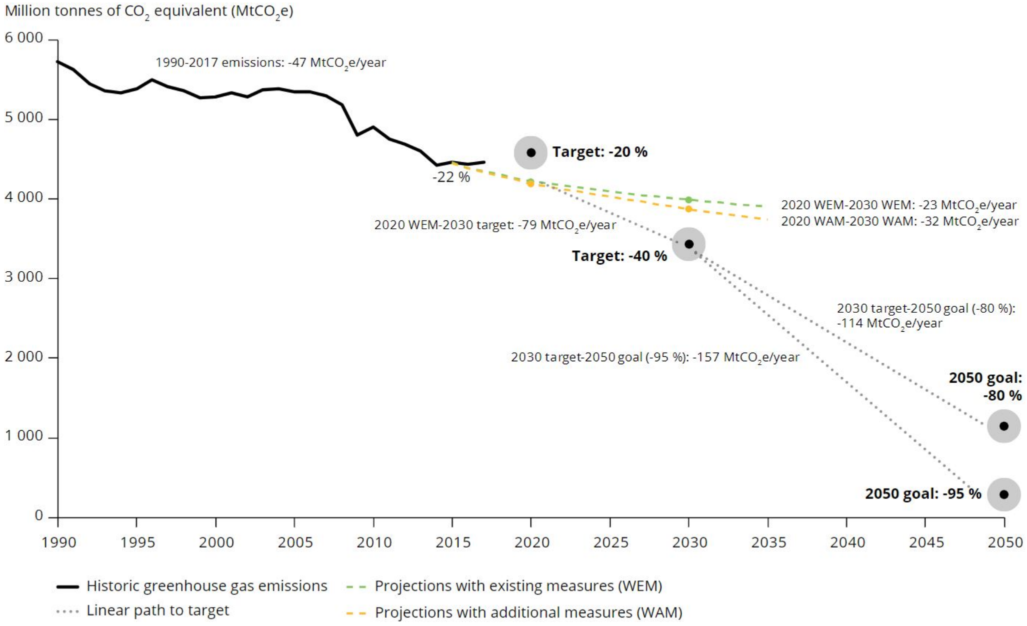


Figure 1: Greenhouse gas emission trends, projections and targets in the EU, 1990-2050 (European Environmental Agency, 2018b)

A mitigation pathway consistent with the Paris Agreement *"well below 2 °C"* require having CO$_2$ emission reduction from 40 GtCO$_2$ to 5 GtCO$_2$ in 2050 (Jiang, Peters, and Green, 2019). The European Commission has developed several policies and proposals to achieve EU's 2050 targets on climate and energy. The EU addressed the first explicit energy and climate policy package addressing emission reduction and energy sector reform by 2020 target in 2007 (Directive 2009/28/EC). Later, based on this approach and structure, the commission came forward with three strategic road-maps: *The Road map for moving to a competitive low carbon economy in 2050, the Energy Road-map 2050, and the Road-map to a Single European Transport Area – Towards a competitive and resource efficient transport system (COM (2011)112, COM (2011)885, COM (2011)144).* These road-maps present the aspects of the transition to a low carbon economy by 2050, cost-efficient GHG emission reduction milestone for 2030, high energy efficiency, a high share of renewable energy and energy infrastructure development (European Commission, 2018a). The road-maps highlight pathways to reduce the GHG emission to 80% below the 1990 level by 2050 and the contribution of the energy sector towards such decarbonization objectives.

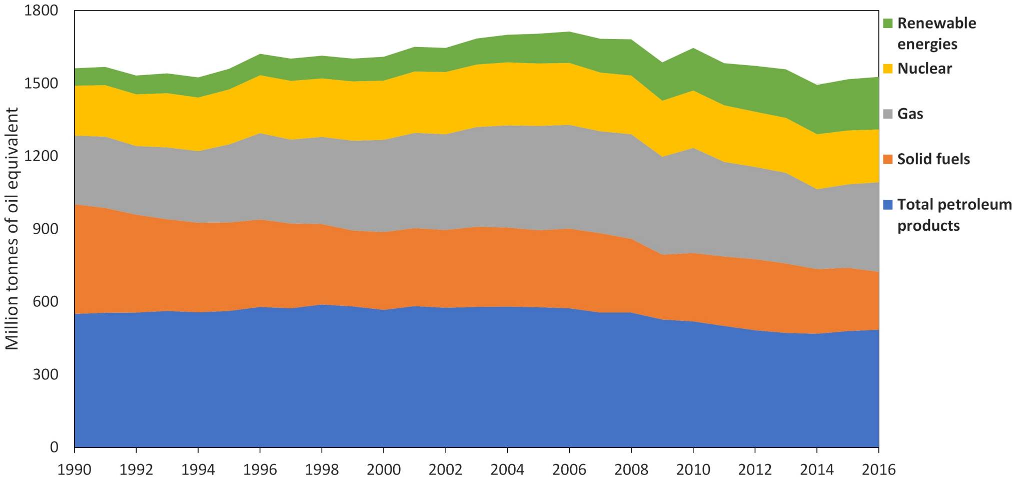


Figure 2: Primary energy consumption by different types of fuel, EU-28 (Data: Eurostat, 2018b)

The spread of fossil-fuel-based energy consumption as shown in Figure: 2. Changing lifestyles is a major driver of global resource use and the main contributor to rising greenhouse gas (GHG) emissions (Barrett et al., 2014). A global pursuit of the Paris Agreement will promote the expansion of these low-carbon technologies. Policies implemented by the EU to mitigate climate change have transformed the energy industry. This has led to the penetration of renewable energy technologies into the energy system (European Commission, 2018b). Consequently, the socio-economic, political and technological feasibility of electricity from wind and solar has enhanced over the years. So such technologies act as the primary player in the energy market. The share of renewables in the gross final energy consumption grew by 9% in 2005 to 16.7% in 2015 (IRENA, 2018). The European Commission projects final energy demand in the residential sector to decrease by 28% by 2050 (compared to 2005). The fossil fuel use falls by 88% and renewable energy production (chiefly from wind, solar, biomass and waste) more than doubles in the same time - driven by the 2030 renewable energy target and competitive renewable technologies costs. The transport sector is the major source of CO_2 emission by 2020 (European Commission, 2018a). Additionally, the electrification in the transport sector could induce huge demands for rare metals such as lithium for the batteries (Ziemann et al., 2018).

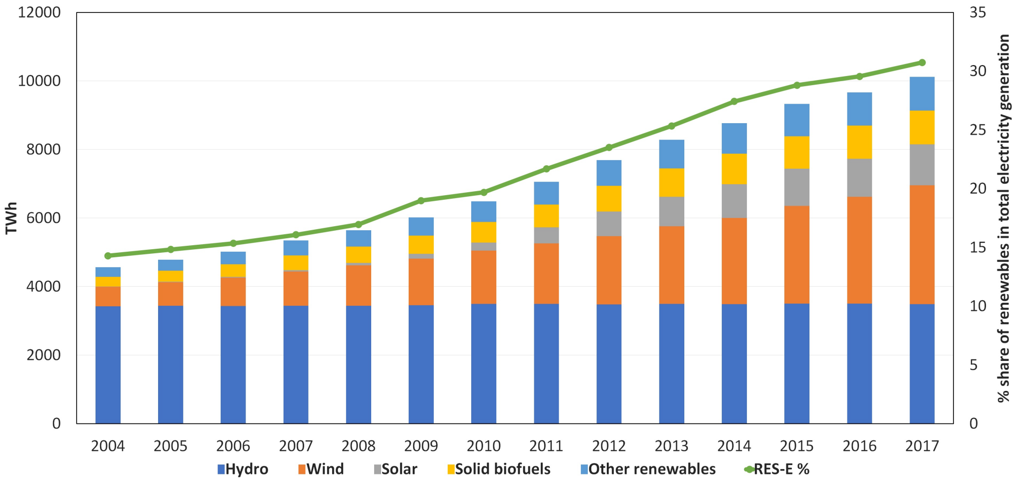


Figure 3: Share of Renewable in Electricity Generation, EU-28 (Data: Eurostat, 2017)

2.1 The EU road map for climate-neutral economy

2.1.1 Scenario Description:

This study mainly uses the European commission scenarios, which are then considered as a guideline to investigate the material required for the transition to a low-carbon energy system in the European Union by 2050. The European Commission strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy by 2050 and the associated work define scenarios that look into how the sectors and the economy can be decarbonized as a whole. The European commission scenarios are developed by PRIMES (Price-Induced Market Equilibrium System) energy system model which was devised by the Energy-Economy Environment Modelling Laboratory at National Technical University of Athens. PRIMES has been used in many studies which look into the long term restructuring of the EU energy system. This involves taking climate change, renewable energy development, energy efficiency, emissions and environmental policies into account(E3M Lab, 2014). Additionally, it includes all sectors and GHG gases, covering not only CO_2 emissions related to energy combustion but also CO_2 process emissions (emissions due to a chemical reaction) and emissions of CO_2 of the land use sectors, non-CO2 emissions of all sectors. The modelling is useful to understand the interaction between the energy sector as well as the interaction of the energy system with other relevant sectors. The PRIMES model explores eight economy-wide scenarios that achieve a different level of emission reduction.

The scenario covers the range of EU's contribution to the temperature objectives of the Paris Agreement *well below 2°C* and *pursuit to achieve a 1.5°C temperature change*. The scenarios present multiple pathways to achieve these goals. For instance pathways that involve energy efficiency by virtue of circular economy and lifestyle change that limits the demands. Also, pathways to decarbonizing the energy supply by switching to carbon neutral carriers like electricity from RES, e-fuels, hydrogen and also use of Carbon Capture and Storage for negative emission. The results of the scenarios are then contrasted to the Baseline *Reference scenario 2016* given by European commission for comparison. The *Reference scenario 2016* as a Baseline scenario, which considering currently proposed policies by the EU and its member states, that continuously reduce GHG up till 2030. The Reference scenario acts as a benchmark of current policies and market trend with a time frame until 2050, which help for future policy debate and policy-making. Furthermore, it is important to note that these scenarios are implemented for GHG reduction post-2030. These scenarios depict a gradual change from the current situation incorporating various mitigation options. Apart from the Baseline, three categories of scenarios are explored which is the foundation for this study, they are:

Baseline Scenario 2016

The Baseline scenario composes of several climate agreements by the members of Commission. The main aspect of the Reference case scenario is that it focuses on the EU energy system, transport and GHG emission trends including non-energy related specific emission. The reference scenario mainly focuses on the trend and projection, not the forecast, in other words, the EU reference merely provides a model-derived simulation of one of its possible future state conditions. The baseline projects the achievement of the energy and climate 2030 targets of at least 40% GHG emissions reduction compared to 1990, at least 32% renewable energy share in final energy consumption compared to 2007, as agreed in June 2018. The modelling suits used are based on an interlinked model of technical and economic methodologies. The models only represent the state as defined by respective assumption, and the projections are subjected to uncertainties.

First Category of Scenario

The first category focuses on a reduction of greenhouse gas emission approximately 80% compared to 1990 and the *well below 2°C ambition* in Paris Agreement. There are five scenarios explored in this category. The scenarios are based on the implementation of improvement in energy efficiency, and high development of renewable energy as well as enhancement of transport system efficiency. Three of the scenarios are mainly driven by decarbonized energy carriers as described before, which also examines the shifting from fossil fuel to carbon neutral carrier viz. *electric (ELEC)*, *hydrogen (H2)* and *e-fuels (P2X)*. The rest of the two scenarios analyse how well the *Energy Efficiency (EE)* measures and transformation to a more *Circular Economy (CIRC)* can commit towards the desired emission reduction goals. The *Power-to-X (P2X)* and *hydrogen (H2)* scenario which is supported by decarbonized energy carrier is selected from the first category for this study.

Second Category of Scenario

The second category consists of only one scenario, that serves a bridge between all of the five scenarios in the first category of scenario. The COMBO scenario combines criterion from all of the five scenarios from category 1 with further GHG reduction higher than the well *below 2°C* goal. The outcome of this scenario is net GHG emission reduction to 90% by 2050. The main aim of the scenario is to identify to what extent emission reduction can be achieved combining all the technological solutions from different scenarios.

Third Category of Scenario

The first and the second category will further undertake the effort to reduce emission only after 2050, that result in the trend of GHG emission towards zero. The third scenario category aims the highest GHG reduction and achieving net-zero emissions by 2050 with support from negative emissions regarding the Paris agreement's ambition, *limiting 1.5 °C temperature change,* . There are two scenarios incorporated in this category. The first scenarios *1.5TECH scenario* aims to increase the use of all technological options and is more dependent on the deployment of biomass with integrating a lot of carbon capture and storage, (BECCS: Bio-energy carbon capture and storage) to reach net zero emission in 2050. On the other hand, the second scenario *1.5LIFE scenario* it does not rely on technological use like *1.5TECH scenario* but is it is more inclined to drive the EU business and consumption pattern to a more Circular economy. Additionally, *1.5LIFE scenario* involves an increase in climate awareness among the EU citizen to change their lifestyle and consumption that is beneficial for the climate, for example: more efficient consumption of foods and energies for heating and cooling system. The *1.5TECH scenario*, chosen from the third scenario category for implementation in this study, because of its high technological penetration (wind energy and electric vehicles) to achieve the net-zero emission goal by 2050.

2.1.2 Power sector

The EU energy supply projections evolve both in terms of its overall level and the energy mix. The projected baseline achieves 26% reduction in 2030 and further 35% reduction in 2050, compared to the primary energy consumption in 2005. The energy production is estimated to decrease by 28% compared to 2005. The fossil fuel production drops nearly 88% and the renewable energy mainly solar, wind and biomass doubles as it is driven by 2030 RE target and competitive RES cost. The electrification of different industries demands the increase in the production of electricity, mostly because of the transport sector witnessing electrification of rail and gradual penetration of electric vehicles. The growth in electric vehicles (electrification of the transport sector) will accelerate the demand for power (Kleijn et al., 2011). In the EU power generation mix projection that favours renewables generating 73% of electricity by 2050, compared to with wind energy being most significant. At the end of 2016, the total installed capacity for the EU power generation was 989 GW (Eurostat, 2018a). The GHG emission accounted for due to power generation was approximately 1,08 $GtCO_2$-eq in the year 2016 (Eurostat, 2018a).

2.1.3 Transport sector

The EU commission has shown that passenger transport activity still grows continuously, particularly for passenger cars in the Baseline Scenario. However, the share of vehicle stock categorised by types of propulsion can be varied relative to the criteria used in each scenario. For example, the policies aim to change the transport system such as mode shift, and increase the efficiency of public transports can slow down a necessary for owning the vehicle which can be seen in Figure 4. This action shows the trend of transport activity in Baselines scenario and in other scenarios aiming to reach -80% to net zero emission by 2050. Therefore, this may affect the electric vehicle adoption in the coming year. Furthermore, other drive-trains apart from ICE, especially electric motor, are influenced by an improvement of technologies and infrastructure for charging the battery electric vehicle. According to the European Commission, the internal combustion engine vehicle seems to be increasingly used with high CO_2 standard for the heavy vehicles after 2020 without further go above the current level.

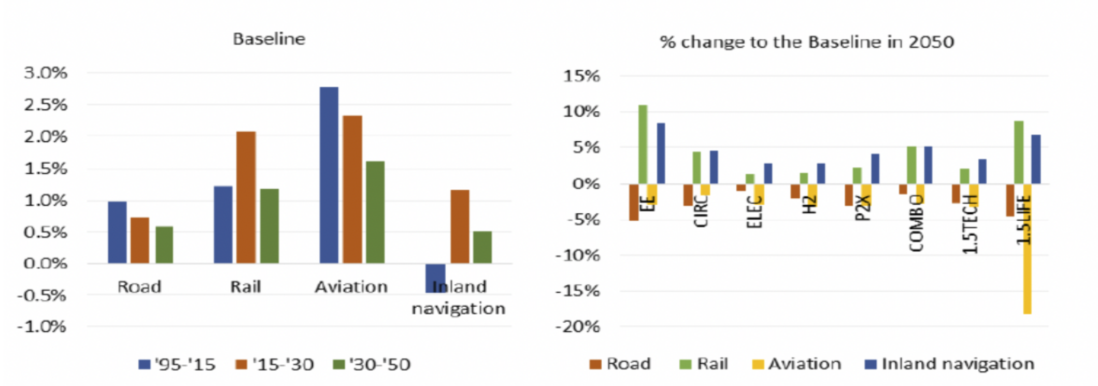


Figure 4: Passenger transport activity in the Baseline scenario (average growth rates per year) and in -80% to net zero emission (% change to the Baseline scenario in 2050) (European Commission, 2018a)

By 2050, the battery electric vehicle will share 35 % of the total stock while the share from conventional diesel and gasoline passenger vehicles will drop from 42% of the total stock in 2015 to 20 % by 2050, for diesel vehicle, and from 54% in 2015 to 18 % by 2050, for gasoline vehicle. These trends are caused by the lower costs of technologies which attracting the consumers. Moreover, the higher shares for battery electric vehicle stock will appeal in the scenarios aiming -80% to net zero emission target by 2050 compared to the Baselines. For example, the P2X scenario has a share of about 47% of the total stock from the battery electric vehicle. However, this shows the lowest number among other studied scenarios. The reason behind this is that the P2X scenario aims to utilise an e-liquid fuel in the internal combustion engine for CO_2 reduction instead of changing to the alternative drivetrain. In the case of the COMBO scenario, the share of the battery electric vehicle is approximately 56%. For the scenario with an ambitious goal to reach net zero emission by 2050, the 1.5TECH scenario presents the highest share of the battery electric vehicle at around 80% of the total stock.

2.2 Steelmaking technologies

The steel production is counted as an energy-intensive industry due to the material extraction, material preparation, and material transformation to steel which contributes approximately 7% of the total emission in the EU (European Commission, 2018a). Steel production can be categorised into two types, which are the primary steel production and secondary steel production. The primary steel production refers to the steelmaking process that uses raw materials to produce steel. In contrast, secondary steel production needs steel scrap for crude steel production. In general, the quality of steel produced by secondary steel production will depend on the quality of steel scrap. This thesis, it will focus on different steelmaking technology as well as their primary energy consumption along with the CO2 emissions. Various steelmaking technologies are explained in the next subsection.

2.2.1 Blast furnace (BF) and Basic Oxygen Furnace (BOF)

In the current EU steel industry, the main primary steel production comes from the BF and the BOF, which is the most energy-intensive process regarding a transformation of the raw material from iron ore to iron (Arens et al., 2017). First of all, the iron ore is melted inside BF, and the hot metal is sent to BOF. After that, the crude steel comes out from BOF. Furthermore, BF/BOF requires a good quality of iron ore and coking coal for its processes (European Commission, 2013) . Nevertheless, some fraction of iron scrap can be used in BF/BOF. The production of BF/BOF contribute the most CO_2 emission compared to other steel routes.

2.2.2 Electric arc furnace (EAF)

Most of the secondary steel production comes from EAF. This steelmaking technology relies mainly on recycled scrap availability and small portions of raw materials (Egenhofer et al., 2013). As a result, this steel production process helps to reduce the need for primary resources. The major energy carrier used in EAF is electricity. Therefore, the CO_2 emission from EAF is depended on sources used for the electricity generation. However, secondary steel production is limited by the availability of scrap (Arens, Worrell, and Schleich, 2012)

2.2.3 Direct reduction iron (DRI/EAF)

There is another route to produce primary steel by using DRI. Sponge iron is generated for an iron reduction process by using a hot gas (Hydrogen and Carbonmonoxide). Natural gas is used in this process to generate hydrogen. Then, the sponge iron is melted together with the scrap in the EAF. Comparing to BF/BOF, DRI emits less CO_2 when primary energy used in the process is based on natural gas instead of coal. The DRI is then mostly installed in countries with plentiful reserve of natural gas (Moya and Pardo, 2013).

Currently, only one DRI plant is in Europe, which locates in Germany (Arens, Worrell, Eichhammer, Hasanbeigi, and Zhang, 2017).

2.2.4 Hydrogen Breakthrough Iron making Technology (HYBRIT)

The HYBRIT's concept is the zero-carbon steel production by using hydrogen gas in the reduction of iron ore. The hydrogen reacts with the iron oxide and creates water instead of CO_2. The process of iron production is similar to DRI. The only difference is the hydrogen gas is used in the reduction process instead of natural gas. The hydrogen gas is produced by electrolysis of water using the electricity generated from fossil-free sources mostly by wind energy, solar and biomass with carbon capture and storage. As a consequence, the entire process is fossil-free or carbon neutral. (HYBRIT, 2017).

2.3 Wind energy as the future of renewable energy

The need for a low carbon economy for there reasons of energy security and environmental impacts is high. This will promote the penetration of renewable energy source to supply electricity into the grid, in and around the globe. In the European context implementation of the wind power is fastest among all the RES (Alexendra et al., 2016). Kleijn et al. (2011) also state that wind power plays a vital role in decarbonizing the economy, in other words, a renewable based economy. Similarly, many studies organisations such as IRENA in the EU energy prospect report also emphasises and predicts the growth of wind to make the EU power sector to more RES based. Within Europe like Germany, Denmark, the UK and Sweden sighted the noticeable growth of wind energy and net annual installation. IEA expects wind power to become the main source of power in Europe by 2027 also EU Commission believes that it could meet more than half of Europe's power demand by 2050 (Wind Europe, 2017). Wind Europe (2018) central scenario, IRENA (2018) and European Commission 2018a) predicts the capacity to rise around 320-350 GW compared to 189 GW in 2018 to achieve 35% RES share. Similarly, the IEA Sustainable development scenario predicts the wind capacity around the world to grow around 2819 GW by 2050, where electricity generation by wind in Europe is 1558 TWh (IEA, 2018b). Also, one of the most important trends is the larger range of Wind turbine gives manufactures to choose designs that yield low Levelized Cost of Energy (LCOE). This makes the Wind energy as the most viable renewable option for the future.

2.3.1 Components of a Wind turbine

The basic purpose of a wind turbine is to harness the kinetic energy to mechanical energy and then to electricity. There four main components of a wind turbine as shown in Figure: 5:

Rotor The rotor consists of an aerodynamic device that is connected to the blades, which spins a generator to produce electricity. The rotor is connected to a shaft that transfers the rotational force to the gearbox in the nacelle (World Steel Association, 2012).

Nacelle The nacelle is the housing that mainly protects the key components attached to it. The nacelle encloses the electrical generator, the gearbox. The size of the nacelle is big enough for service personnel to enter it for maintenance. The rotor blades are attached to the nacelle. It weighs around 100-150 tons on an average for a 1.5MW turbine (Hollaway, 2013).

Tower The tower of the wind turbine carries the nacelle and the rotor. The tower's tubular structure is mainly made of high-grade steel with concrete and steel foundation. The height of the tower currently ranges between 25-130m. The higher towers are used for the larger turbine with higher capacity so that the blades can sweep more area to produce more electricity (Hollaway, 2013), (Wind Denmark, 2017).

Rotor Blades The rotor blades are connected to the rotor and are responsible to capture the wind capture and transfer of power to the rotor hub. The length of the blades depends on the size of the turbine and the tower height. The rotor diameter can be from 20m to 125 m in some in larger turbines, to maximise the yield. (World Steel Association, 2012)

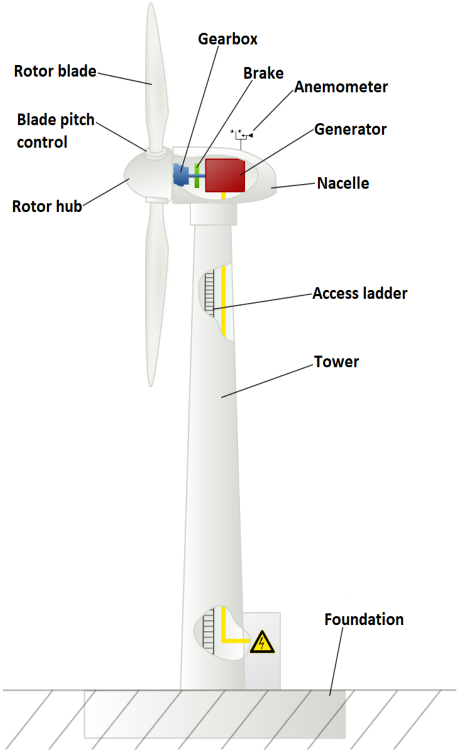


Figure 5: Main components of a Wind Turbine

2.3.2 Offshore and Onshore Wind

Wind turbines can be classified on the basis of location, drive train technology and converter size. In this study, we only look into the classification based on the location namely offshore and onshore. As is evident from the nomenclature, onshore turbines are the ones located on the land and offshore are the ones located away from land mainly in the sea. The commercial onshore wind turbines range from 1MW to approximately 4.8 MW (GE Renewable Energy, 2017). In the past years as per IRENA (2018), the onshore wind installed costs have reduced so the growth in the onshore wind has risen significantly. Similarly, to harness the high wind speeds offshore wind turns out to be more efficient. A significant development in the size of the turbine has led to access to deeper waters with high wind speed (IRENA, 2018). The EU commission in the climate neutral Europe report and IEA in the the world energy outlook 2018, projects that the offshore wind has a lot of potential for growth in the EU like it has seen on the past decade. Many of the innovative wind energy systems proposed to target the offshore wind market due to their more economical and high power generation (Siemens Gamesa, 2017). Unlike the onshore turbine, the offshore turbine has various foundation designs based in the depth of water, jacket, tripod, monopile and floating (World Steel Association, 2012). The jacketed and monopile, are the most common types of foundation, operating at water depth ranging between 30-60 meters. So the offshore wind is more steel-intensive creating a trade-off between size and steel usage. In the recent years, many projects have been proposed within EU to operate in deeper water in the Mediterranean off the Iberian coast and the North Sea which will have to be floating foundation rather than fixed (European Commission, 2018a). The EU aims to install around 350 MW of floating offshore wind capacity by 2021 which can accelerate later.

2.4 The battery electric vehicle (BEV)

The transport sector causes around one-quarter of the EU's CO_2 emission (European Environmental Agency, 2016b). As a result, the EU Commission created the goal to reduce 65% of CO_2 emissions from passenger vehicles by 2050 compared to 2005. Therefore, a BEV is promoted for achieving this ambition because BEV does not have an emission through an exhaust pipe-line compared to combustion engine but it needs the electricity for regular charging an installed battery in the vehicle. The main components of BEV, which are different from an internal combustion engine vehicle (ICEV) will be further explained in the following paragraph:

Electric motor: Compared to the internal combustion engine vehicle (ICE), BEV uses chemical energy stored inside the installed rechargeable battery as an energy source to power an electric motor instead of using liquid fuels, petrol, and diesel to power the piston engine. Also, the electric motor can regenerate the electricity back to the battery while the vehicle decreases its speed during the break.

Comparing to the combustion engine, the electric motor operates more efficiently than the conventional engine since there is less loss compared to the engine thus BEV has the most efficient drivetrain systems (European Environmental Agency, 2016b). Furthermore, the electric motor requires less maintenance than a conventional engine (Morris, 2015).

Batteries: BEV uses the battery to store energy that powers the vehicle. In current battery technology, lithium-ion batteries are the most common type of battery used in BEV (Dinger et al., 2010). The advantages of the lithium-ion batteries apart from other types are its high energy capacity storage and longer lifetime of the battery. However, the drawbacks of lithium-ion batteries are its heavy weight and expensive cost of production, which is around 40% more expensive than the Nickel batteries (Notes, 2018).

Controller: The purpose of the controller is to regulate the function of both the electric motor and the battery by governing the power supply from the battery to the electric motor.

Regenerative brake: With the regenerative brake, the energy, which may be lost during braking, can be converted back to the electricity and sent back to the battery. Therefore, the higher efficiency of the electric motor can be obtained with this device.

Since a BEV is fully electrified, the amounts of CO_2 emission depend on how the electricity is produced (Gaines et al., 2012). This can create a pathway to sustainable transport and a benefit to the environment if the electricity come from renewable sources. Therefore, the sources of the electricity generation mix need to be considered. Although the electricity is produced from the high penetration mix of renewable energy including fossil fuels, few emissions still occur (European Environment Agency, 2016a). Even BEV contribute no emission during its use phase, some of the consumers still prefer to drive ICE due to the limitation of driving-range of BEV and long period for recharging the battery. As a result, the large capacity of the battery is generally required to further extend the driving range of BEV. This will add more weight to the vehicle which affects energy consumption.

3

Methodology

The primary aim of the study is to determine the steel demand for wind energy and battery electric vehicles in the EU until 2050. The next focus is the quantification for CO_2 emissions associated with the steel demand for both technologies and the EU steel industry. The final purpose is to develop various pathways based on the share of the different steel making process in order to examine the least carbon-intensive route. The intended aims were achieved by the three parts:

1. Investigate the future wind capacity and penetration of BEV based on the projected data by EU commission scenarios and respectively develop growth pattern.
2. Calculate the annual steel demand for wind energy and BEV using:
    (a) Annual growth rate of wind capacity and vehicle stock
    (b) Steel content per unit of wind turbine and BEV
3. Quantifying the CO_2 emission by:
    (a) Devise different pathways based on the share of steel making technologies
    (b) Calculating the emission factor for the energy carries in the steelmaking technologies using compond annual growth rate
    (c) Compare the cumulative CO_2 emission from the steelmaking to the EU carbon budget.

The scenarios from the EU commission selected for the analysis are reviewed in order to investigate the future demand for wind capacity and penetration of BEV. With projected penetration for wind energy and BEV, the steel required by these two technologies is calculated with material flow analysis. Then the CO_2 emissions associated with the steel production for wind energy and BEV are investigated. This is performed by developing the steelmaking pathways based on different steelmaking technology mix, i.e., BOF/BF, EAF, DRI/EAF and HYBRIT as described in the section 2.2.

3.1 Growth pattern

The growth pattern for various technologies can be modelled by various methodologies. Many studies examine future growth patterns at a time of growing uncertainties since the global energy system is changing (IEA, 2018b). The growth pattern varies in different climate stabilising scenarios since the model used in various scenarios analysis varies widely in the resolution of different energy technologies (Wilson et al., 2013). Historical growth rates in energy production can be generalised to predict the future growth pattern, which is described as “forecasting analogy” by Hook et al. (2012). The most elementary method would be extrapolating the percentage increase in the installed capacity taking market share into account based on the final capacity stated in the scenario which is more of an exponential pattern (Elshkaki et al., 2013).

3.1.1 Logistic Growth

A way of studying the dynamic growth model in technologies are the exponential and logistic growth model. In the exponential growth model, the variable grows slow in the beginning and but it rapids up as time increases. It does not take any constraint into account and hence leads to an unbounded growth with a J shaped curve. The key concept of exponential growth is that the capacity growth rate increase as the cumulative capacity gets larger. Many studies like Kleijn and van der Voet (2010), Jacobson and Delucchi, 2011 and Kramer and Haigh, 2009 demonstrate the exponential growth pattern where the capacity of technologies increases exponentially. Hook et al. (2012), states all unbounded growths trend towards infinity and are clearly not viable in the long term as it depends on an infinite amount of resources.

On the other hand, the bounded growth model or Logistics growth model is the one subjected to a limitation that affects and leads to slow growth in due course of time (Hook et al., 2012). The bounded exponential curve or Sigmoid curves follow a slow growth at the beginning and end hence making it easier to fit the real implementation of technology and dynamics of the economy and market. Generally, the limiting factor lies in the form of high monetary, energy or resources required for further expansion. Sigmoid curves are used in many research fields, for example in biology where it is used to describe population growth. Davidsson et al. (2014) state that in studies such as Hook et al. (2012) and Wilson et al. (2013) point out the reality of growing systems which is eventually subjected to limitation. This limitation makes the growth stagnant over time and asymptotically strive towards the maximum value that brings out an S-shaped curved called logistic curve for a most dynamic system. The limiting factor lies in the process itself like increasing cost, restrictive policy, limited resources for further expansion Hook et al. (2012). The equation below shows the Bounded exponential curve or Logistic function:

$$y = \frac{C}{1 + Ae^{-Bx}} \tag{3.1}$$

Equation: 3.1 involves three parameters A, B and C., In this case, the C is the final capacity or the asymptotic, x being the time, B is the diffusion rate or the carrying capacity which determine the steepness of the curve. This implies that if B is positive the logistic function will increase on the other hand function decreases if B is negative. To identify the exact meaning of parameter A we set $x = 0$ in Equation: 3.1 we find that

$$y(0) = \frac{C}{1 + Ae^{-B\times 0}} = \frac{C}{1 + A}$$

This gives the equation *(1+A) y(0) = C*, one way to interpret it is the limiting value of C is *1+A* time larger than the initial output *y(0)*. In other words, A is the number of times that the initial capacity must grow to reach C. Another important feature of any logistic curve related to its shape, the logistic curve has a single inflexion point which separates the curve into two equal regions of opposite concavity. It is easy to identify the precise coordinates of this inflexion point: because of the symmetry of the curve about this point, it must occur halfway up the curve at height. Setting y equal to $\frac{C}{2}$ in Equation: 3.1 :

$$\frac{C}{2} = \frac{C}{1 + Ae^{-Bx}}$$

$$A = e^{-Bx}$$

$$Bx = \ln A$$

$$x = \frac{\ln A}{B}$$

This shows that the inflection point has coordinates $\left(\frac{\ln A}{B}, \frac{C}{2}\right)$. If we can determine the coordinates of inflexion points using this the value of B can be calculated.

3.1.2 Compound Annual Growth Rate

The growth pattern for various technologies can be modelled by various methodologies. Many studies examine future growth patterns at a time of growing uncertainties since the global energy system is changing (IEA, 2018b). The growth pattern varies in different climate stabilising scenarios since the model used in various scenarios analysis varies widely in the resolution of different energy technologies (Wilson et al., 2013). Historical growth rates in energy production can be generalised to predict the future growth pattern, which is described as “forecasting analogy” by Hook et al. (2012). The most elementary method would be extrapolating the percentage increase in the installed capacity taking market share into account based on the final capacity stated in the scenario (Elshkaki et al. 2013). The other means of examining the future growth patterns is the Compound Annual Growth Rate (CAGR). CAGR assumes that the variable grows at a constant rate of return compounded each year over a period, in this case, the time frame is assumed until 2050. CAGR is mathematically represented as

$$CAGR = \left(\frac{EndingBalance}{InitialBalance}\right)^{\frac{1}{Numberofyears}} \tag{3.2}$$

CAGR is representation figure that describes the rate at which a variable, in this case, the wind capacity and electric vehicle adoption would grow at the same rate every year and the excess increment was accounted each year (Investopedia, 2019). But, this kind of growth pattern is unlikely doesn’t consider and it is evidently seen that CAGR calculates a smoothed rate of growth over a period, without taking market and technological volatility into account. Additionally, the growth patterns are uneven over time and CAGR infers the steady growth during that time, which are the main constraints of using CAGR to examine growth pattern in energy technologies.

3.2 Material Flow Analysis

A material flow analysis (MFA) is aimed at analysing material flows and stocks in the system based on a mass balance between inputs, stocks, and outputs within a society (Müller et al., 2014). Additionally, the MFA can be utilised for both sources and individual materials (Park et al., 2011). In this thesis, the MFA will associate with steel flow due to the deployment of wind power and passenger BEV. Therefore, the supply chain of steel will include the input & output flow for BEV and wind energy, for off-shore and on-shore, to the stocks according to the new productions and end-of-life of products. Furthermore, the results of MFA can be used to increase the efficiency of steel usage in the EU, i.e., supporting the information for impact assessment and resource comparison (Allesch and Brunner, 2017). The MFA will take as a point of departure from the scenarios developed in the EU Commissions ‘A Clean Planet for all’ report European Commission (2018a) and also explore a range of other scenarios describing how the transition of the EU energy system may affect the steel flow (Kleijn et al., 2011). Emphasis will be on quantification of anticipated steel used for the wind energy and BEV in the low-carbon scenarios regarding the EU commission.

3.2.1 Steel and iron production

In this process, the raw materials for steel production are identified corresponding to the demands for BEV and wind energy each year. The dynamic of the material production continues by adding the material, iron ore and steel scrap from recycling, to the processes. Following Rootzén and Johnsson (2016), the steel production chain was separated into four steps: (1) the iron and steel process; (2) the finishing process; (3) the fabricating and manufacturing process; (4) the consumption. Furthermore, the data of steel production are extracted from national statistics. The overall system boundary for this analysis is illustrated in Figure 6.

3.2.2 BEV

Vehicle stock

The dynamic stock of BEV is developed similarly as the methodology of Ziemann et al., (2018) and Modaresi and Müller (2012). The parameters required for stock calculation in each year include the population of European Union countries from 2017-2050 as projected by the United Nation for the studied time-frame and the numbers of vehicle ownership per capita. The EU population data used in this

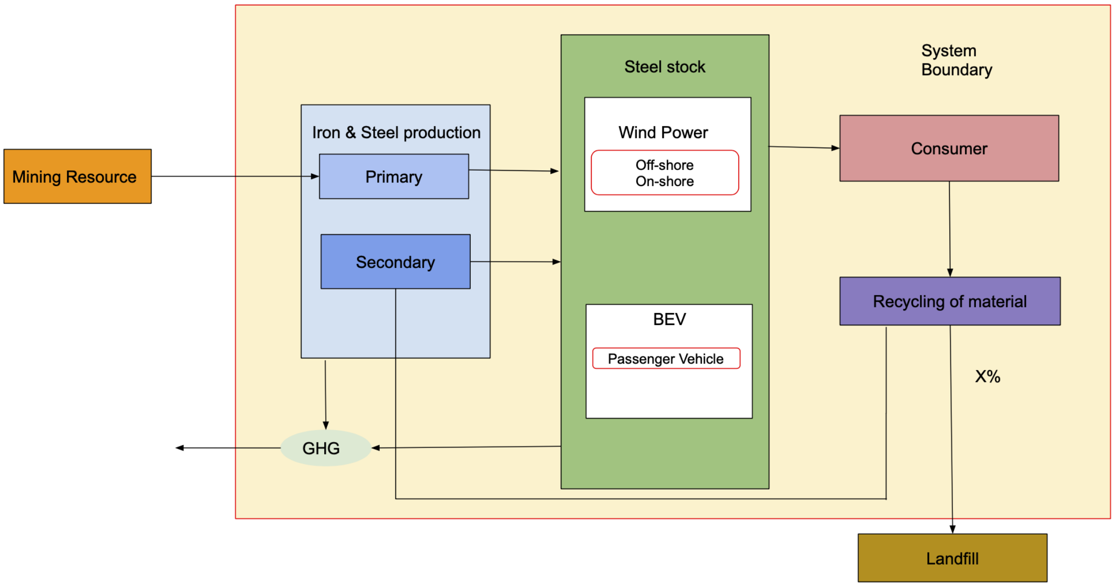


Figure 6: System boundary of the analysis

study is based on the medium scenario. However, the increasing or decreasing population number may also affect the results. Therefore, the high population scenario and low population scenario projected by the United Nation will be also investigated in order to explore the variation of the results. The BEV adoption, for passenger car, in each year is assumed to follow along with the logistic curve, which is also considered in the study of Kushnir and Sandén (2012), and will reach the specific fleet projected by European Commission (2018a) in 2050 for different scenarios including the Baseline scenario, as shown in the Figure 7. The chosen low-carbon scenarios for the analysis from the commission are P2X, COMBO and 1.5 TECH which were discussed in " The EU road map for climate-neutral economy" section. The relation between each parameter is shown in the following equation:

$$S_t = P_t * N_t * V_t \tag{3.3}$$

The parameter S_t, P_t, N_t and V_t represent the stock of vehicle, the projected population, the vehicle ownership per capital and the BEV adoption respectively. The parameter t stands for the considered year.

As previously mentioned, the stocks of the electric vehicle can be computed by using the simplistic relation between the number of populations, vehicle ownership and the BEV adoption on each scenario. According to Figure 6, the inflows of steel production come from primary and secondary steel. However, for this study, the estimation for steel demands disregard a quality of steel, which may be made from the secondary and primary steel, but only consider a quantity of steel consumption.

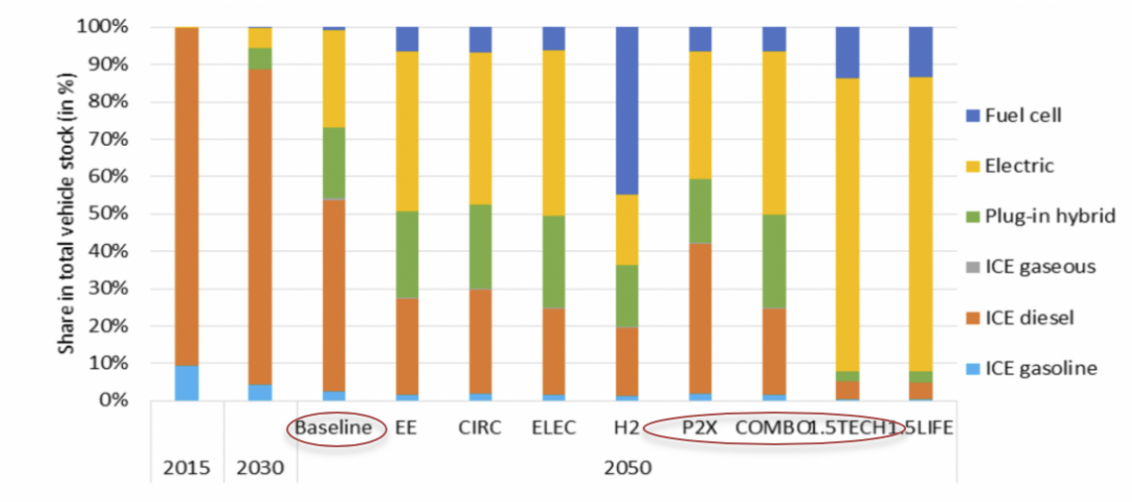


Figure 7: Projection of the BEV stock (European Commission, 2018a)

Steel stocks for BEV

Regarding the total BEV stock, the relative stocks of material can be determined by multiplying the total amounts of material composted inside the BEV with the total BEV stock as the following equation:

$$X_t = S_t * M_t \tag{3.4}$$

The parameter X_t and M_t express the stock of steel and the total steel contented in the BEV respectively.

The material compositions inside the BEV can possibly alter due to the purposes of weight reduction, fuel saving and limiting CO_2 emission (Lewis, Kelly and Keoleian, 2014). Also, several studies of material compositions in the vehicle have been reviewed and revealed that different types of bulk material were used, especially the lightweight material (Mayyas et al., 2018; Milovanoff et al., 2019 and Luk et al., 2018). This implies that the steel contents in the BEV may vary between different BEV models. Therefore, the various references can diversify the investigated results of material requirements in the BEV regarding the different material compositions in particular vehicle models which also shown in Figure 8. However, for this study, the steel compositions in the vehicle data are scrutinised from the vehicle model developed by Luk et al., (2018), which adjusts the vehicle specification of GREET (Argonne National Laboratory, 2016) and further categorises them into different power trains, however, only BEV will be considered in this study. Additionally, steel contents in the BEV are assumed to be constant over the considered timeframe for a simplification.

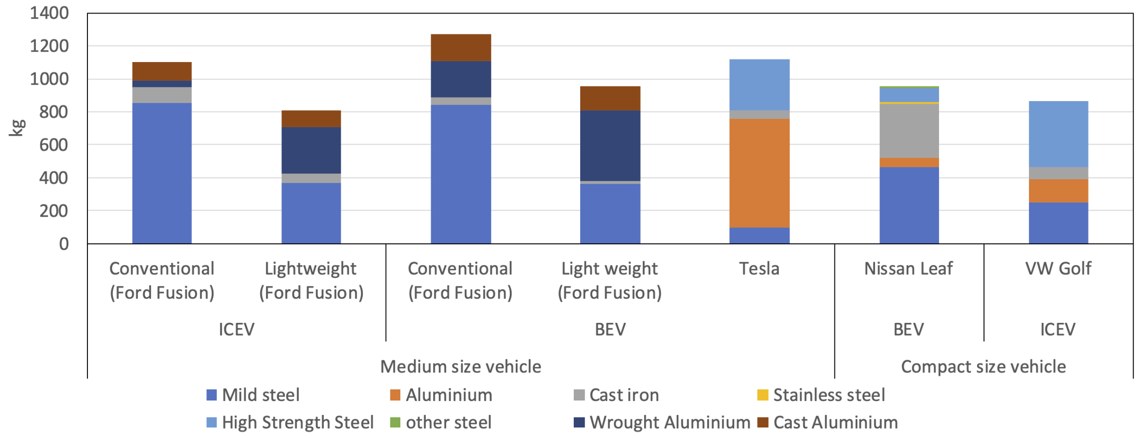


Figure 8: Bulk material compositions in different types of vehicle and brand (Mayyas et al., 2018 , Milovanoff et al., 2019, Luk et al., 2018 and REUTERS, 2018)

The steel breakdown used in this analysis is traced into different parts from the BEV models developed by Luk et al., (2018)), which is the conventional BEV. The vehicle model was categorised into drive-train, power-train, body/body in white, chassis and gliders. The drive-train, excluding the engine or motor, has a function to deliver power to the driving wheels. The power-train includes motor and also the drive-train. The body-in-white contains all components which are assembled together. The chassis is the frame of a vehicle which helps to support and tolerate the stresses on cars. For the glider, it can be recognised as the vehicle regardless of a power-train. The material breakdown used for this analysis is summarised in Table 1

Table 1: Steel content for the selected BEV model used as a base case in this study which investigates into different components of vehicle (Luk et al., 2018)

Component of the BEV	Steel, kg
Body	566
Chasis	198
Motor	36
Electronic Controller	4
Transmission	73
High Voltage Battery	13

Annual steel demands for BEV

With developed steel stocks for BEV, the annual steel demands are basically derived by subtracting the stocks of steel composed inside the BEV in the current year with the previous year. In this respect, the following equation shows the determination of annual steel required for new BEV in a unit of million-tonnes (Mt):

$$Y_t = X_t - X_{t-1}. \tag{3.5}$$

Where Y_t presents the annual steel demand for new BEV.

The actual annual steel demands can be possibly overlooked in case that an end of life vehicle (ELV) is neglected since the old vehicles need to be replaced with the new ones after its end of life. This implies that more materials will be required to build new vehicles. Witkamp et al., (2017) used the economic vehicle lifetime of 15 years to investigate the impact of a transition to a zero-emission vehicle fleet by 2050. Furthermore, the study of Cabrera Serrenho and Allwood (2016) stated that the vehicles have been scrapped at the lifetime between 10-13 years. Another factor that could limit the overall lifetime of BEV is the battery pack used in BEV which cans range between 5-20 years (Ziemanna et al., 2018). Regarding previous studies, this thesis assumes that BEV and the battery pack will have the same lifetime of 11 years so that the steel demands for replacing ELV can be investigated. Furthermore, the high vehicle lifetime scenario and low vehicle lifetime scenario will be explored in order to understand the effect of this parameter on the steel demands. The following equation shows how to compute the steel demands for ELV (A_t).

$$A_t = Y_{t-T} \tag{3.6}$$

Where parameter T represents the lifetime of the BEV. Thus, the steel demands for ELV will be added up with the annual steel demand for new BEV giving the net annual steel demand. The below equation shows how to calculate the net annual steel demand when considering the end-of-life vehicle.

$$Net\ annual\ steel\ demand = A_t + Y_t. \tag{3.7}$$

The net annual steel demands are compared to the total crude steel consumption within the automotive industry of EU in 2017 and assumed sustaining the same amounts of consumption until 2050. The purpose behind this comparison is to investigate whether the future materials required in the BEV will exceed current consumption in the automotive sector for the upcoming transition to low carbon energy systems by 2050 or not. Furthermore, this aims to explore the share of future steel used by BEV comparing to other steel requirements in the automotive sector.

In actual situation, the steel used in different parts of the vehicle can possibly be produced from the sources outside the EU, thus the exact quantities of steel required for the increasing BEV penetration can be variable and depend on the amounts of import and export. However, in this study, the vehicle manufacturer is assumed to be consuming the steel produced from the steel plants in the EU.

3.2.3 Wind Energy

The electrification of different industries demands the increase in the production of electricity, mostly because of the transport sector witnessing electrification of rail and gradual penetration of electric vehicles. The growth in electric vehicles (electrification of the transport sector) will accelerate the demand for power (Kleijn, 2011). In the EU power generation mix projection that favours renewable generating 73% of electricity by 2050, compared to with wind energy being most significant. At the end of 2016, the total installed capacity for the EU power generation was 989 GW (Eurostat, 2018b). The CO_2 emission accounted for due to power generation was approximately 1,08 Gt CO2-eq in the year 2016 (Eurostat, 2018b). At the end of 2016, the total installed capacity for the EU power generation was 989 GW (Eurostat, 2018b). The CO_2 emission accounted for due to power generation was approximately 1,08 Gt CO2-eq in the year 2016 (Eurostat, 2018b).

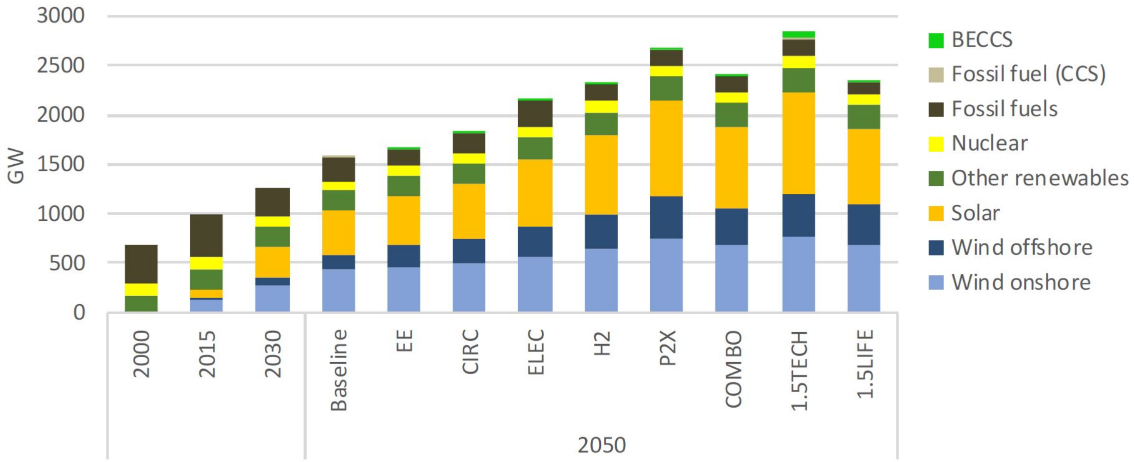


Figure 9: Power generation capacity in different scenarios (European Commission, 2018a)

Wind power generates around 11.5% of electricity in 2017 and 55% of newly installed capacity (Wind Europe, 2017). Technological advancement has led to the improved capacity factor of the reduced cost of wind energy technologies. The EU is a global leader in wind energy integration with offshore wind development being very exclusive to Europe. As per wind, Europe offshore wind could meet the EU electricity demand and onshore could meet twice as much, because of its high resource potential. A total of 11.7 GW (9 GW onshore and 2.65 GW offshore) of new wind capacity was installed in 2018. The total EU-28 wind power capacity in 2018 is 189 GW (171 GW onshore an 18 GW offshore) (Wind Europe, 2018). But for the offshore wind to grow, it must be operated in much deeper water, with turbines floating rather than fixed. Despite higher growth rates in electricity production globally by wind energy, it remains intermittent. Many studies predict that the global energy system would be based on solar and wind by 2030 to 2050, the assumed capacity for solar varies from study to study. But the wind capacity remains the same around 19-24 TW (Davidsson et al. 2014). In this study to determine the growth pattern and material consumption in EU wind energy by the end of 2050, scenarios from the EU commission report has been referred.

Scenario Description

To perform a quantitative model-based analysis based on macro-economic analysis eight economy-based scenarios attaining a different level of CO_2 emission reduction are explored. These scenarios explore the potential CO_2 emission reduction as per the Paris agreement objectives. The scenarios depict several pathways like the use of negative emissions, technology to decarbonize energy supply (fuel switch to more carbon-neutral carriers like electricity from RES, Hydrogen, e-fuels) and moderation of demand (via circular economy or change in lifestyle leading to energy efficiency). These scenarios are compared to baseline projections. For the reference case, a baseline scenario was implementing form the EU reference scenario 2016 which illustrates the trend of Energy, transport, and CO_2 emission until 2050.

The aim of the Baseline is to illustrate the impact that current climate and energy policies and goals would have on long-term energy and CO_2 evolution. (Ref 2016). Hence, it gives a basis for comparing different long-term pathways consistent with targets limiting global warming to well below 2°C or 1.5°C. The Baseline has been specifically built to the development of the long-term strategy.The EU reference states that Wind provides 14% of total net electricity generation in 2020, 18% in 2030 and 25% by 2050. 24% if the total generated from offshore wind capacities i.e. approximately 33 GW. Due to the high cost of offshore wind, its market penetration is limited compared to onshore wind in the Baseline. Thus, by the end of 2050, the offshore wind capacity is 150GW only 11GW increase compared to 2030. So, the total European Wind capacity increases to 207 GW in 2020, 350 GW in 2030 and finally to 587 GW in 2050.

Table 2: Wind capacity in 2050 for various scenario (European Commission, 2018a)

Scenarios	Onshore, GW	Offshore, GW	Total, GW
Baseline	437	150	587
Energy Efficiency	465	235	700
COMBO	700	350	1050
1.5TECH & P2X	800	400	1200

European Commission, (2018a) states that Wind capacity increases in 2050 from some 140 GW in 2015 and some 350 GW in 2030 to between some 700 GW (EE) and some 1200 GW (P2X and 1.5TECH) in scenarios achieving 80% CO_2 reduction and 1.5TECH scenario goes slightly higher to over 1200 GW, meaning a further doubling to tripling compared to 2030, which corresponds to annual installation of some 30 GW (EE) to over 50 GW (1.5TECH) between 2030 and 2050 (Figure: 10), hence exceeding in most scenarios the average pace observed over 2000-2015 for the entire power capacity (31 GW/year). The onshore wind would represent close to two-thirds of total wind capacity in 2050 (92% in 2015): from 460 GW (EE) to 760 GW (1.5TECH).

Comparing primary energy consumption (PEC) projections to its historical 2005 levels, the Baseline achieves 26% reduction in 2030, 35% reduction in 2050 and there are no further reductions by 2070 as the continuous effect of energy efficiency policies is counterbalanced by effects of economic growth on energy consumption. Some scenarios emphasise energy supply technologies, such as renewable, nuclear power, bioenergy or carbon capture and storage. Other scenarios depict widespread diffusion of end-use technologies that improve energy efficiency or shift the types and amounts of energy services demanded in buildings, transportation systems, or industrial facilities. Most scenarios focus on both efficient end-use and energy supply technologies (Future capacity growth, 2013).

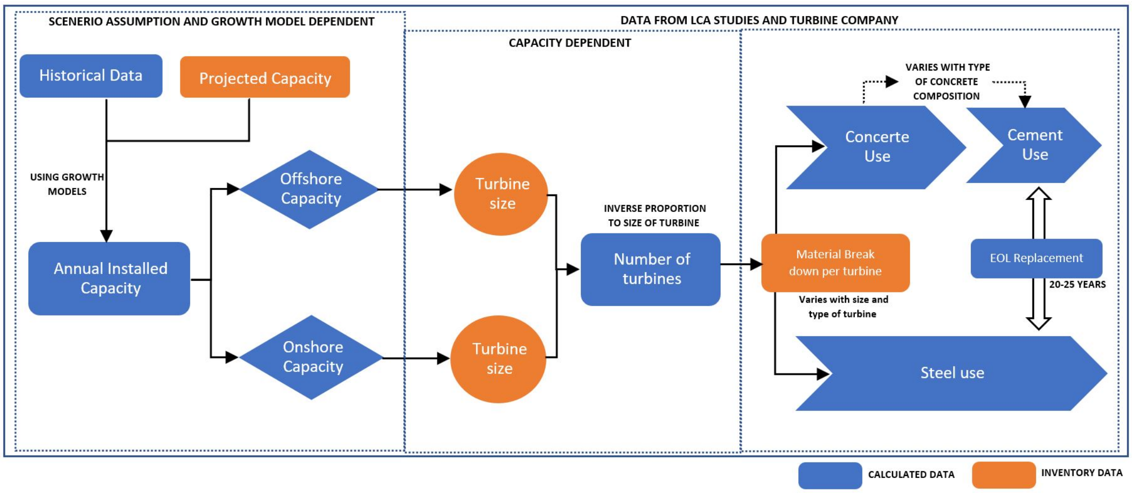


Figure 10: Calculation Description

Material Use

A transition to a low-carbon based power generation would require a substantial upscaling of current mining of several metals. (Kleijn, 2011). The logistic growth model gives the total annual wind capacity additions needed to reach the proposed capacities along with onshore and offshore additions. To quantify the actual steel demand we investigate the inventory data of several LCA. The annual material demand is a function of the technical specification of the offshore and the onshore wind turbine installed annually, the number of turbines installed and the material content in each turbine (Alexandra et al., 2016). The basis of the calculation is dependent on the size of the turbine installed and it's material content.

The present turbines have a capacity of around 1–8 MW on land and up to 3–12 MW for offshore sites. The calculation has been performed based on the average size of a wind turbine and its corresponding material content. The method of calculation has been represented in Figure: 10. The calculation can be summarised as:

- Determination of annual capacity growth (onshore and offshore) from the growth curve
- Based on rated power of turbines calculate the number of turbines installed annually
- Multiply the number of turbines to steel content per turbine (ton of steel/turbine)
- Add the additional steel demand as per End of life/service life of turbine

Table 3: Material Use in larger Wind turbines (**Vestas4MW; SIEMENSlca** Alexandra et al., 2016)

Type of Turbine	Capacity, MW	Concrete, t	Steel, t
Onshore	4,2	1860,75	628,2
Offshore	8,00	121,08	1100

Table 4: Material Use in smaller Wind turbines (Alexandra et. al., 2016; Zimmermann et al., 2013; Vestas, 2014)

Type of Turbine	Capacity, MW	Concrete, t	Steel, t
Onshore	2,00	916,64	335,23
Offshore	4,00	47,71	647,88

An indication of the material used in the turbine is given in the Table: 3 and Table: 4 . The steel required for onshore and offshore wind turbine based on an LCA study by Alexandra et al. (2016) is 167 tons/MW 161 tons/MW of steel and 458 tons/MW & 20 tons/MW of concrete respectively. Similarly, the steel content in onshore and offshore wind turbine twice the size is 150 tons/MW & 137 tons/MW of steel (Vestas, 2014; Siemens Gamesa, 2014). Furthermore, Davidsson et al. (2014) examines the reasonable service life in various LCAs and mentioned that 20-year service appears the most reasonable. In this study, we assume different service life of a wind turbine regardless of its location as 20, 25 and 30 years. The approximate steel content in wind turbines with for various rated power considered by different studies are shown in Figure: 11. This implies that after the end of life a wind turbine, a new turbine of the same capacity must be installed to maintain the production level. A sensitivity analysis can be made based on turbine size different service and its corresponding material use to investigate dependency and trade-off between the size of the turbine to its material consumption.

The further scope of the study is to determine then cement used in the construction of wind turbines the composition of concrete should be known. The cement content in concrete depends on the extent to which alternative cementitious binder is used now and it further depending on the availability, market acceptance and national price standards (Proske et al., 2013).

3.2.4 Variation of Annual Steel Demand

There are a lot of uncertainties in the results obtained as they are based on many assumptions. So changing one of the input parameters can have a different effect on the annual steel demand. In this study, it is very important to examine the influence of these parameters namely the size of the turbine (proportional to steel content) and service life of the turbine. Therefore, the analysis is performed to explore the possible outcomes that may occur with every changing parameters.
The final steel consumption for the wind energy system is a function of turbine size as well as the lifetime of a wind turbine, both of these factors are important for this study. Many studies like (Alexandra et al., 2016), (Zimmermann et al., 2013) and LCA reports form World steel, SIEMENS, Vestas show that the average lifetime of a wind turbine is 20-30 years. Additionally, many of these studies point out that in course of time the turbines are getting larger in size with higher lifetime, for instance, the SIEMENS Gamesa with capacity 10 MW has an approximate life span of 25-30 years. The offshore wind had seen larger turbine to harness the wind speed which is relatively higher than onshore. But there is always a trade-off between the size of the turbine and material use. A representation of the steel content in wind turbine both offshore and onshore turbine can be seen in figure:

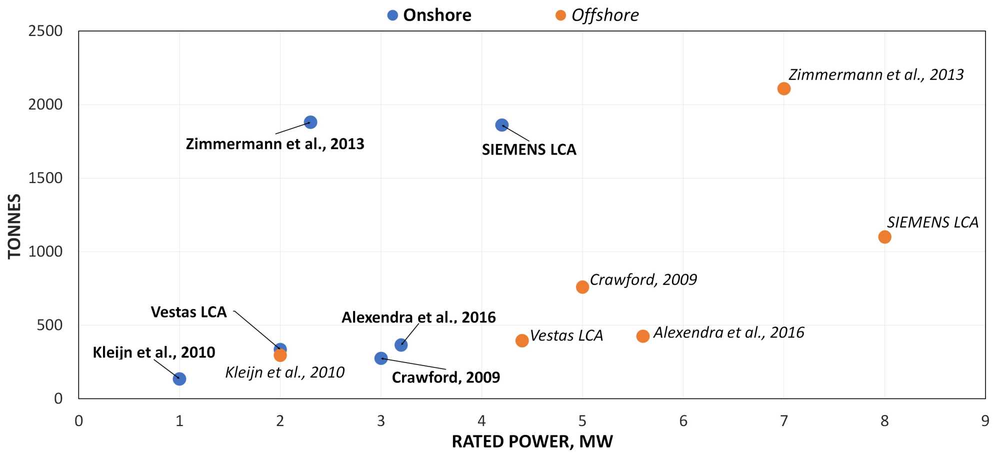


Figure 11: Steel content in wind turbines as per various studies

The steel content is directly proportional to the size of the turbine. The smaller turbines have lower Steel/MW compared to larger ones. But service life can be an important factor that can change the steel demand in terms of future perspective. To analyse variation in annual steel demand we consider the scenario 1.5 TECH scenario as the wind power is the highest by 2050. Figure: 11 shows the steel content in Wind turbine of various capacities in different studies. For the calculations, we use the base case of steel content from Alexandra et al. (2016) for both onshore and offshore as shown in Table: 3. And for the extreme case we use the data from Vestas LCAs for onshore and SIEMENS LCAs for offshore as shown in Table: 4, since they have the highest steel use. Additionally, we make two cases as shown in Table: 5 for different turbine size with altering service life or End of life of the turbine and examine the results of steel demand.

Table 5: Variation of lifetime for 1.5TECH scenario

	EOL, years	**Turbine**
Case I	20, 25, 30	Smaller Turbine
Case II	20, 25, 30	Larger Turbine

3.3 CO_2 emission from steel production

The steel industry is responsible for major CO_2 emission in the EU (Arens et al., 2017). Thus, increasing steel demands from the low-carbon technologies, BEV and wind power, implies additional CO_2 emissions. Therefore, in this section, the CO_2 emissions from the steel production for BEV and wind are determined. By accessing into different steel making technologies, the CO_2 emissions per ton of steel for each technology are explored based on CO_2 emissions from primary energy consumption. The emission factor will be used to compute the CO_2 emission associated with the produced steels in 1.5TECH scenario for BEV and wind energy.

3.3.1 CO_2 emission from different steel making technologies

To identify CO_2 emission related to steel production, the total energy consumption per ton of steel is required. This information was extracted from the study of Arens et al. (2017). The energy consumption of steel production is based on specific types of energy carrier, which includes hard coal, coke, oil, natural gas, oxygen, and electricity in this investigation. The emission factors of each steelmaking technology for different scenarios were computed by using relative energy consumption and specific emission factor of energy carrier used in the steel process. For every energy carrier except the electricity, the emission factors associated with those energy carriers are assumed to be constant and presented in Table 6. Also, the electricity consumption of each steelmaking technology is shown in Table 7. For the case of electricity, the emission factor will depend on the emission from the electricity generation. Furthermore, the electricity used in the steel plant is assumed that it comes from a grid. The emission factors for the electricity generation are analysed based on the transition of electricity production to low-carbon emission grid as per the scenarios expressed in the EU Commission (2018a). Electricity as an energy source is consumed significantly in both primary and secondary steel production, which affects the CO_2 emission factor of steel production depending on the sources of the electricity generation. Determination for the emission factors of electricity will be described in the next paragraph.

Table 6: Emission factor of each steelmaking technology regardless the emission factor from the grid (Arens et al., 2017 and HYBRIT, 2017)

Emission factor, kg CO_2/t of steel						
Technology	**Hard Coal**	**Coke**	**Oil**	**Nat. Gas**	**Oxygen**	**TOTAL**
BOF	329	1154	34	96	82	1695
EAF	11	0	0	67	31	109
DRI/EAF	9	0	0	947	34	990
HYBRIT	0	0	0	0	25	25

Table 7: Electricity consumption of steel making technology (Arens et al., 2017 and HYBRIT, 2017)

Technology,	**Electricity, kWh**
BOF	115
EAF	739
DRI/EAF	819
HYBRIT	3488

Gross electricity production

The projection of power sector from the Baseline scenario presents that the gross electricity generation will reach the level of 4600 TWh by 2050, in which 73% of the total generation is produced by renewable energy sources (European Commission, 2018a). Therefore, CO_2 emissions from the electricity generation will decrease to 208 Mt of CO_2 by 2050. The increasing electricity generation is caused by the demands for electrification of rail and high BEV fleet. In the low-carbon scenarios, the electricity demands are projected to increase for all of the decarbonisation scenarios by 2050. Higher electricity demands will occur in every sector compared to the demand in 2030, especially for the transport sector in 1.5TECH and ELEC scenarios (2017). With this reason, the gross electricity generation is expected to be higher in 2050 compared to 2015, which can be seen in Figure 12.

Shifting to high penetration of renewable energy sources and improving efficiency in the power sector in European contribute to less emission from the electricity generation (Teske, Sawyer and Schäfer, 2015). Similar trend is observed in the European Commission (2018a), the increasing share from renewable energy sources from 30% in 2015 to 81%-85% in 2050. As a result, the CO_2 emission from the power sector is drastically reduced low levels between 10 MtCO_2 (EE) to 110 MtCO_2 (ELEC) in the low-carbon scenarios. Furthermore, in 1.5TECH scenario, the negative emissions of 140 MtCO_2 are possible due to a capable use of carbon capture storage (CCS) combined with biomass power generation.

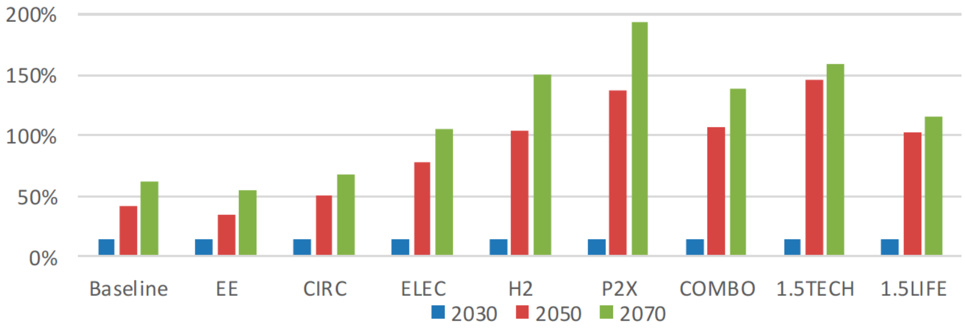


Figure 12: Gross electricity generation compared to 2015 of power sector (European Commission, 2018a)

CO_2 emission from the electricity generation in the European Union

As previously discussed in Section: 3.3.1, the annual electricity generation and CO_2 emission is projected based on specific amounts of total power generation (Figure 12) and CO_2 emission of each scenarios starting from 2018 to 2050 by assuming the projected values will follow along the compound annual growth rate until 2050. Therefore, an average emission factor from the electricity production is derived by dividing the total emission has unit $kgCO_2$ from the power sector with the total electricity production in kWh. As a result, the emission factor from the electricity generation has the unit of $kgCO_2/kWh$. The emission factor from the electricity generation in 2018 until 2050 is determined regarding the previously mentioned methodology for every scenario.

With these computed emission factors, the annual emission factors of Baseline scenario and low-carbon scenarios are obtained, which based on the specific annual CO_2 emission of the power sector and the annual electricity generation of each scenario. The specific emission factor from the electricity usage in steel production is acquired by multiplying total electricity used in the steel process with the calculated emission factor from the public grid. The effect of emission factor of the electricity grid to the emission factor of the steelmaking technology will depend on the total electrical consumption for each steelmaking technology. The final step for determination of CO_2 emissions from the steel processes is an aggregation of the emission factor from every energy carrier together. The projected gross electricity generation of considered scenarios including the computed results of CO_2 emission of the grid and steelmaking technology will be presented in the Results section.

3.3.2 Pathway towards the decarbonization of the EU steel industry

In steel industry of EU, the current share between primary steel production (BOF) and secondary steel production (EAF) is approximately 60% and 40% respectively (European Commission, 2018a). With this information, different shares of steelmaking technology mix are modelled. The reason behind this is to explore an optimal CO_2 reduction opportunity from the steel industry and the effect of implementing scenarios of the European Commission. The various pathways of steelmaking technology mix are developed by considering different types of steel technology such as EAF, DRI/EAF, and BOF/BF. The new emerging low-carbon technology, HYBRIT, also includes in the investigation. Although the HYBIRT technology is estimated to be implemented in 2025 (HYBRIT, 2017), it is assumed that this technology is feasible at the beginning time-frame of this analysis. Each pathway will begin with the current existing steel production (BOF and EAF) in the beginning year of the analysis, then it will be projected to several matches from various steelmaking technology mix to 2050. The developed pathway are displayed in Figure 13. The amounts of steel production are based on the annual steels required in the new wind power and BEV production.

EAF uses the scarp as main input material. Furthermore, the study of Pauliuk et al. (2013) shows that the future scrap supply will rise doubly by 2050, and the secondary steel production will be surplus primary steel production eventually during 2050-2060. Thus, the scrap availability for secondary steel production is assumed to be assured for simplification. As a result, the full capability of secondary steel production can be obtained. With the developed pathways of the steelmaking technology mix, the analysis will further investigate CO_2 emission from the steel industry of EU by exploring the steel production level around 168 Mt of steels in 2018 and assuming constant annual production level during the time-frame of the analysis. The developed pathways are discussed as follows:

- **Pathway 0** sustains the current level of steel making technologies mix (business as usual case) for BF/BOF and EAF until 2050. The purpose of this pathway is to identify the effects if there are no changes in the EU steel industry when more steel demand are expected.

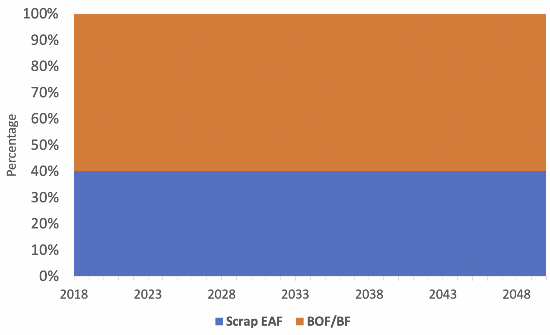
- **Pathway 1** only considers the existing steel making technologies, which are EAF and BOF, and assumes that in the long run higher share coming from the secondary steel production will transpire and replace BOF/BF. There are no other new technologies implemented in this pathway.

- **Pathway 2** further includes DRI/EAF in the analysis comparing to Pathway 1, which assuming an economic condition is suitable for implementing this technology during the studied period.

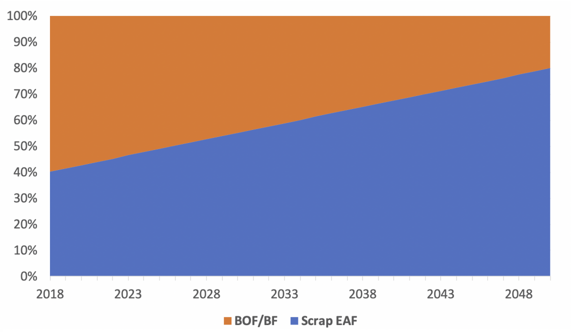
- **Pathway 3** aims to persuade implementing an innovative steelmaking technology, HYBRIT and phasing out BOF/BF by 2050. The primary steel production from any phased out BOF/BF can be substituted by DRI/EAF.

- **Extreme pathway** is developed along with the low-carbon technology, which promotes the lowest CO_2 emission steelmaking technology, i.e., HYBRIT. Comparing to Pathway 3, the extreme pathway assumes that the steel production shared from HYBRIT about 70% of total steel production.

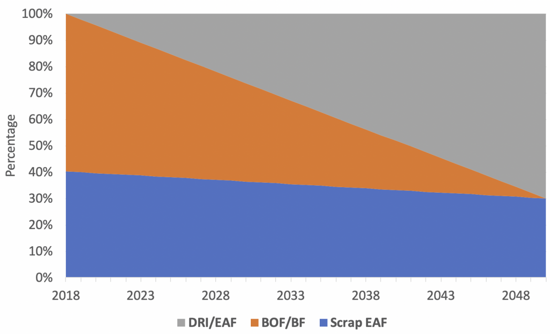
a) Pathway 0



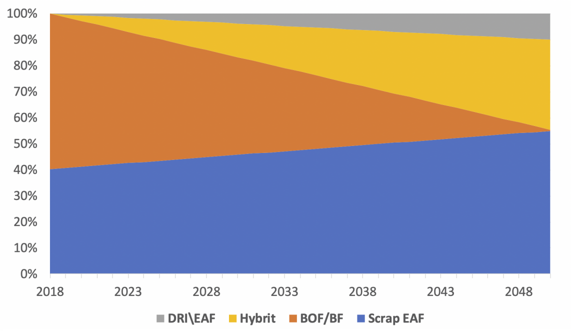
h) Pathway 1



c) Pathway 2



d) Pathway 3



c) Extreme pathway

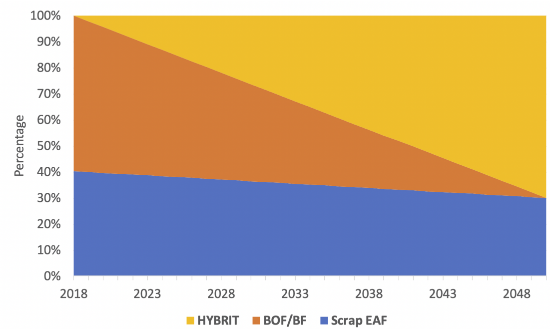


Figure 13: Developed pathways of EU steelmaking technology mix from 2018 to 2050 based on the current steel production and assumptions

4

Results

4.1 Steel required in low-carbon energy system

4.1.1 BEV

The results presented for the steel demand for BEV are based on medium case of the vehicle lifetimes and the EU populations, which use conventional BEV model as a base case. The results for different cases for vehicle lifetimes EU population and vehicle models will be further presented in "Variation of annual steel demand" section.

Material stock of BEV

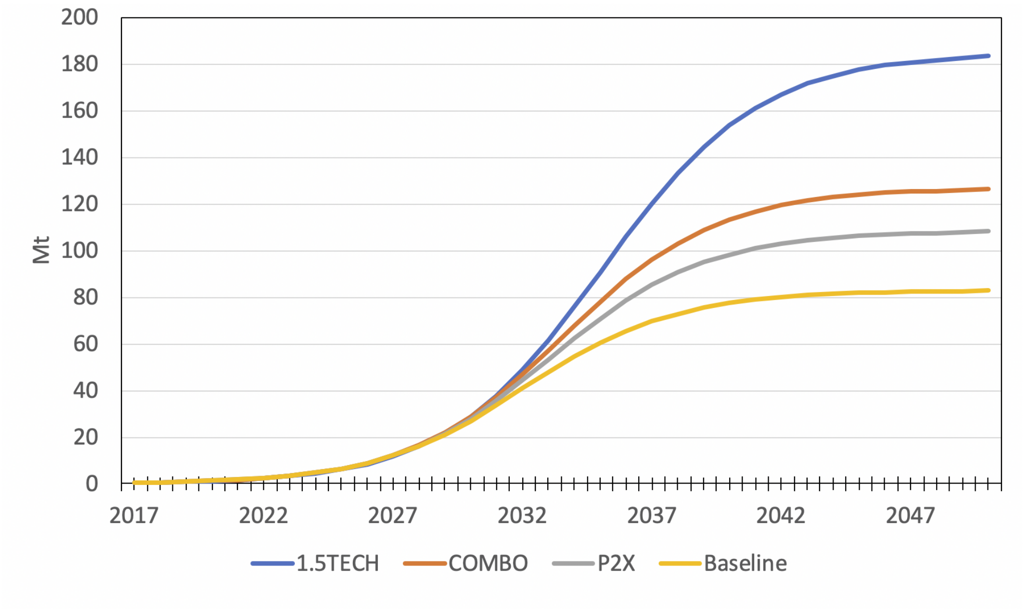
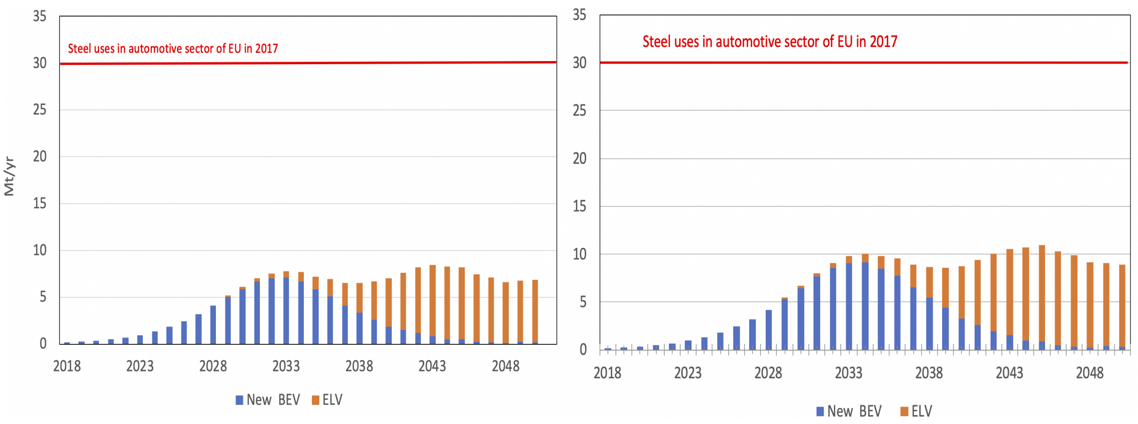


Figure 14: Steel stocks embedded in the BEV for different EU scenarios

Regarding the EU scenarios considered in this analysis, the steels embedded within the BEV stocks are displayed in Figure 14. The results illustrate that scenario aiming for zero CO_2 emission (1.5TECH scenario), in which around 80% of the total vehicle stocks will be the BEV by 2050, presents the highest amounts of steel. This shows the result of large scale availability of charging stations in 1.5 TECH scenario. Furthermore, the major implementation of e-fuels and biofuels in the transport sectors such as road freight, aviation and maritime (European Commission, 2018a), leading to less available options to use in the passenger vehicle. According to low-carbon scenarios described in "The EU road map for future clean climate", the increasing trend of steel stocks in BEV in each scenario slowly deviates from other scenarios at 2030 then reaches a saturated level in 2050.

Annual steel demand


a) Baseline scenario b) P2X scenario

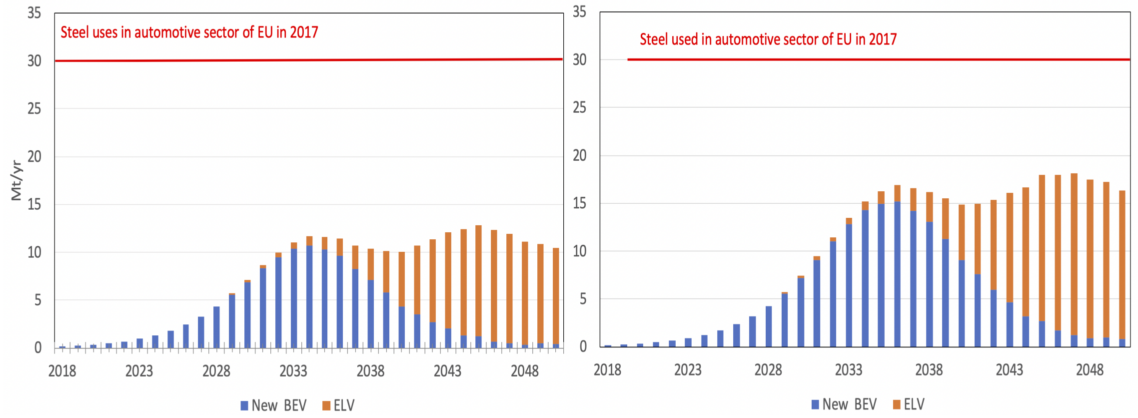

c) COMBO scenario d) 1.5TECH scenario

Figure 15: Total net annual steel demands of BEV for different scenarios comparing to the steel used in automotive sector of EU in 2017.

According to Equation: 3.7, the net annual steel demands for each scenarios are computed and shown in Figure 15. The results show that the steel demands for new BEV continue to rise until 2034 then level off for every scenario after this year. However, the steel demands due to end-of-life occur in 2029 and continue to rise until 2050. The displayed results (Figure 15) inform that 1.5TECH scenario requires the highest net annual steel demands of BEV, following by COMBO scenario, P2X scenario, and Baseline scenario respectively. Furthermore, the peak steel inflow can be observed in 2046 due to a requirement for replacing the end-of-life vehicle. According to this development, there will be an enormous requirement for steel production. Regarding the current steel used within the automotive sector, the steels required of BEV are much lower than the current usage in the automotive sector. From this comparison, the difference between steel used in the automotive sector and steel required for BEV production shows the amounts of steel used by other types of vehicle, i.e., trucks and bus. Therefore, there is no sign of impact regarding the increasing penetration of BEV in the vehicle stock to the steel supply in 2050. According to Figure 15, the ELV refers to the steel need to be reproduced for the new vehicles. Additionally, this also implies a possible opportunity for recycling the steel from the BEV reaching its end-of-life.

4.1.2 Wind Energy

As discussed in the previous sections, wind energy marks significant growth in the future electricity generation capacity in Europe. The material demand for the wind energy system is a function of the total capacity of the wind turbine in the energy system and the size of the turbine. Hence to determine steel used in the wind turbine we calculate the capacity increase of wind annually and its corresponding steel demand and the associated CO_2 emission.

Capacity Growth curves

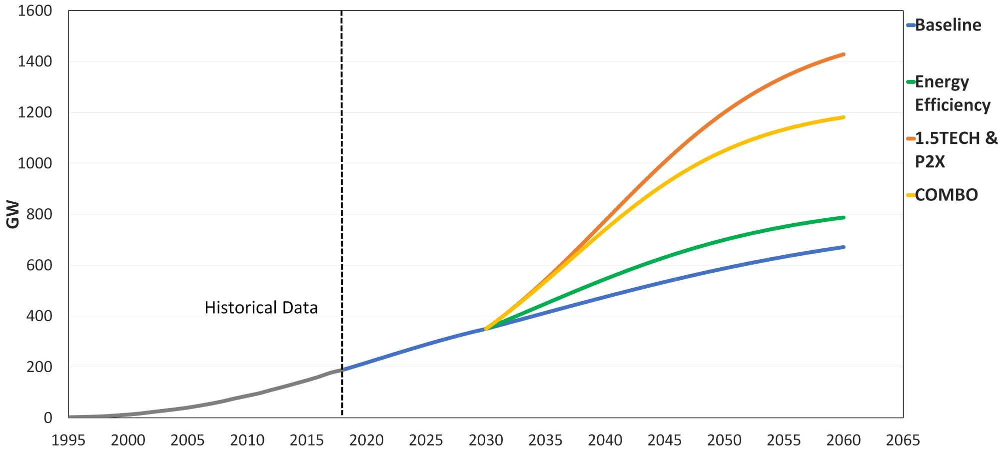


Figure 16: Capacity growth curves for Wind energy in various scenario

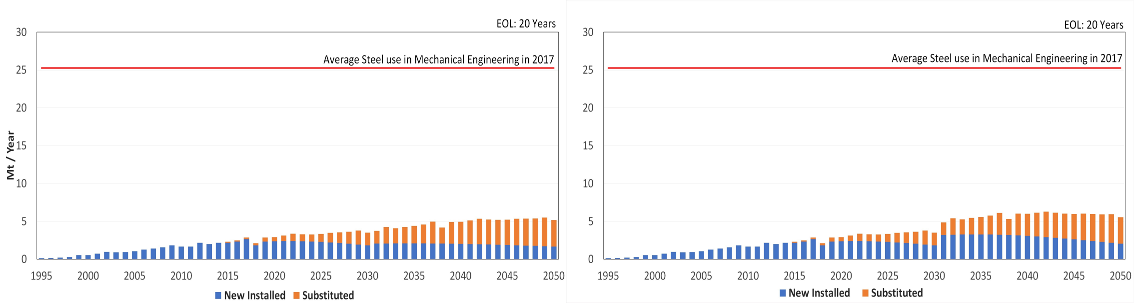
The growth curve model tries to show the pathway or pattern in Wind Energy for various EU scenarios summarised in Table: 2. Using the logistic growth model and the Equation: 3.1 we create the growth pattern form different scenario form 2018-2050. Figure: 16 presents the growth curves of wind capacity, it can seen that the capacity rise occurs after 2030.

As the European Commission(2018a) states that the capacity reaches around 350 GW in 2030, after that due to various scenario implementation and to reach different emission goals, the curve varies. The growth curve is then fitted with the historical data from 1995 to 2018, to see the actual growth pattern. 1.5TECH & P2X scenario reaches the highest capacity of 1200 GW. Even if both 1.5TECH & P2X scenario reaches the same capacity, 1.5TECH is a preferable scenario as the emission reduction will be approximately 90% than P2X which is about 80%.

Annual steel demand

a) Baseline scenario

b) EE scenario



c) COMBO scenario

d) 1.5TECH

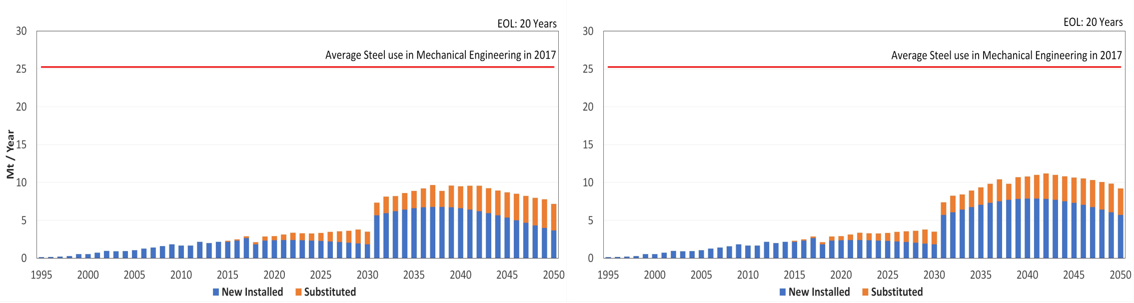


Figure 17: Annual steel demands for the Wind Energy for different scenarios comparing to the steel used Mechanical Engineering sector of EU in 2017

Using the calculation description shown in Figure: 10 and data from Figure: 16 and Table: 4 with 20 years service life of turbine for both onshore and offshore turbine we calculate the annual steel demand. We do not consider recycling in this study to avoid complication rather we only consider the demand for steel to maintain the annual capacity of Wind energy. The steel demand is a function of the capacity growth at a given interval of time, size and service life of a turbine. Thus for different scenarios, we get different results because of the varying capacity growth. The steel demands for various scenarios are shown in Figure: 17. For a metric of comparison of the steel demand, we compare the results with the average steel demand in the Mechanical engineering sector in EU i.e, approximately 25 Million ton. The results obtained are shown in Figure 17.

4.2 Variation of annual steel demand

4.2.1 BEV

Variation of European Union population

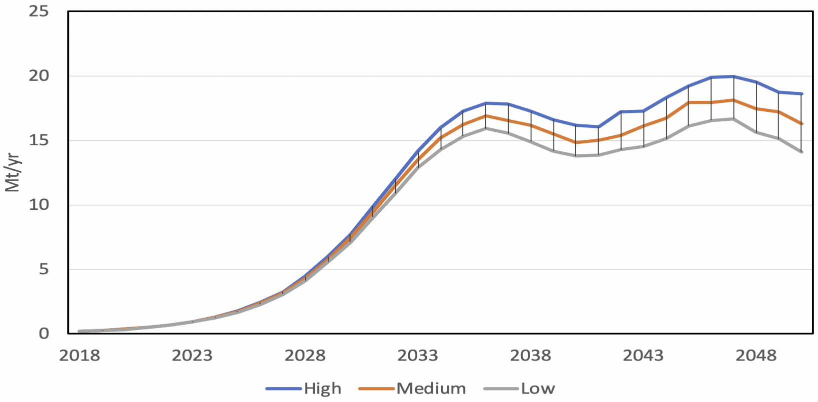


Figure 18: Impact of EU population projection used in the analysis to the results of annual steel demands

The European Union population data used in this study is based on the medium scenario. However, the increasing or decreasing population number can also affect the results. The 1.5TECH scenario was used to analyze the effect of variation on the EU population. The effect of changing the EU population to the net annual steel demands is shown in Figure 18. According to the result, the fluctuation for the net annual steel demands from the medium scenario is approximately 1 Mt of steels.

Variation of the BEV lifetime

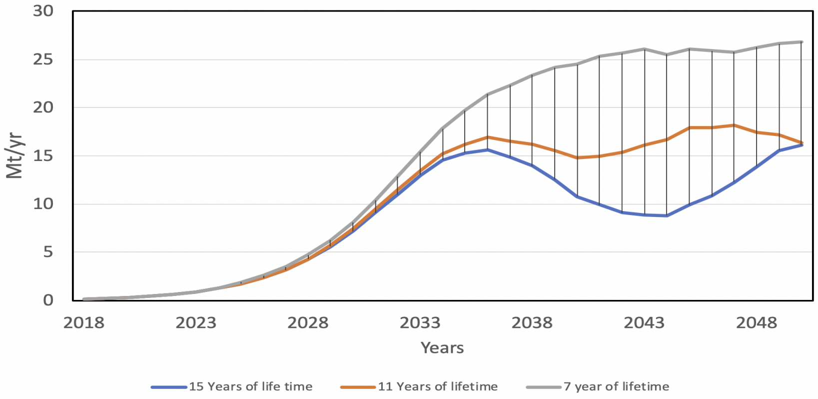


Figure 19: Impact of vehicle lifetimes of vehicle model used in the analysis to the results of annual steel demands

The lifetime of the BEV is the important parameter since the longer vehicle lifetimes, the fewer steel demands will be required. Apart from the base case, the different vehicle lifetimes were assumed and implemented to 1.5TECH scenario for the analysis. The impact of the lifetime is present in Figure 19. The results show that the higher vehicle lifetime, the less steel required for replacing the old vehicles. Furthermore, this indicates that the variation of vehicle lifetime highly influences the results of steel demands. This can be seen from the significant difference in net annual steel demands between 15 and 7 years for vehicle lifetime scenario.

Variation of steel content in the BEV

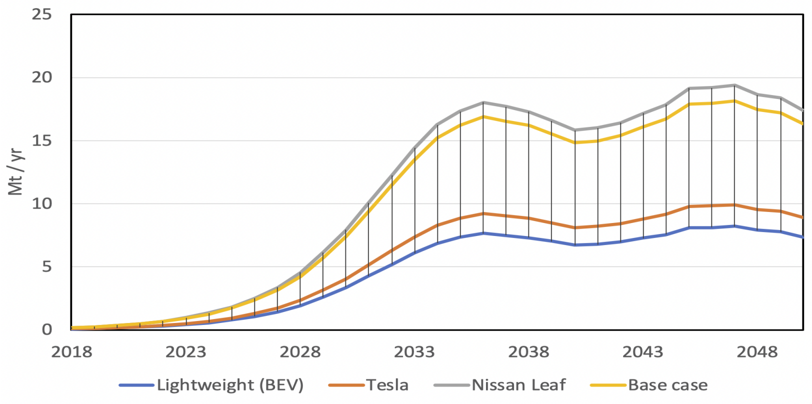


Figure 20: Impact of different steels content in the vehicle model used in the analysis to the results of annual steel demands

As the previous discussion, the different models of the BEV used for the analysis can affect the results of steel demands. The influence of steel compositions in the vehicle is shown in Figure 20. The result illustrates the huge differences in steel demands between the lightweight BEV model and conventional BEV model used in this study. The variation of net annual steel demand begins early in 2022 and increases significantly when the penetration of BEV is higher. This can be concluded that the steel content in the vehicle highly influences the results of the annual steel demand.

4.2.2 Variation in annual steel demand for Wind Energy

The results shown below are basically based on the uncertainties and dynamic parameters such as steel content in turbine and service life of a turbine that can affect the steel used in the Wind energy. These results are based on calculation and certain assumptions that the capacity of the wind grows as mention in 1.5TECH scenario and the turbine size is the same although, as mentioned in the methodology. The results of the variation in the steel demand for the different Cases in 1.5TECH scenario with varying service life are shown in Figure: 21 and Figure: 22. Finally, Figure: 23 shows the two instances among the two Cases where the annual steel demand is highest and lowest. In all the results it can be seen that there is a sudden hike in demand between the year 2030 to 2032, this because of the implementation of the scenario in 2030. The implementation of the scenarios will lead to a rise in the capacity in the 1.5TECH scenario as seen in Figure: 16. Hence, the annual steel demand after 2030 nearly doubles in both of the cases.

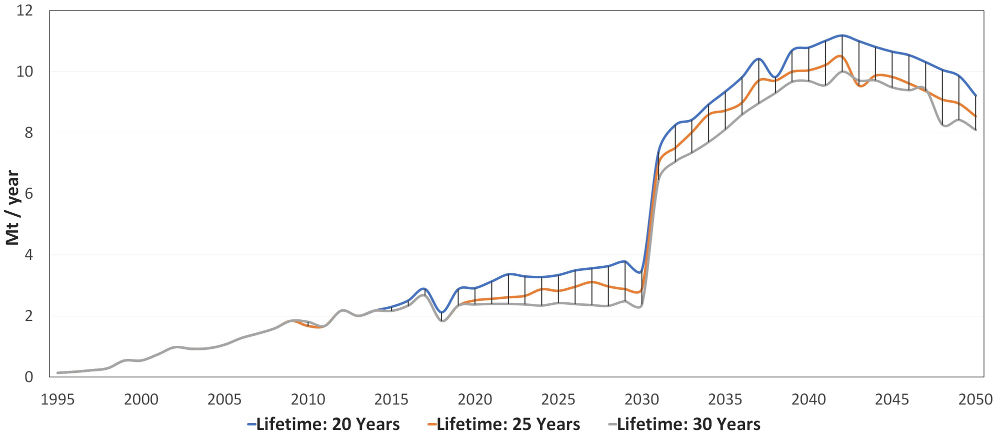


Figure 21: Effect of Lifetime to the steel demand with smaller turbines

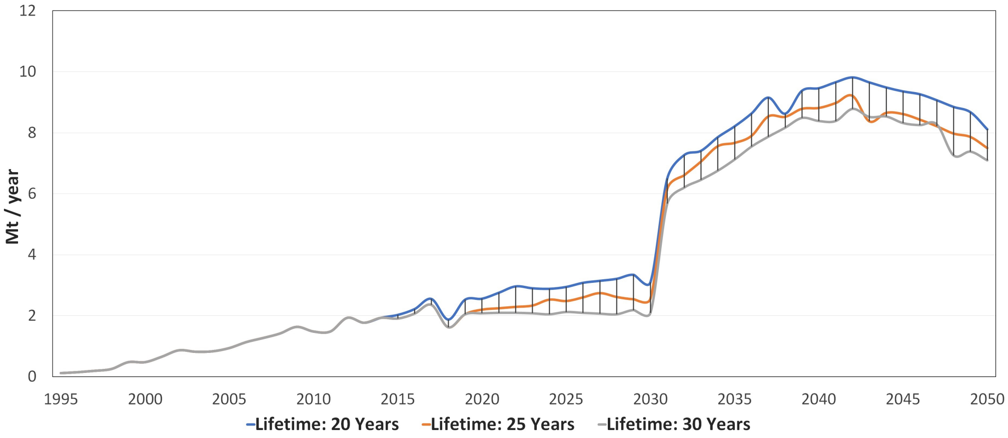


Figure 22: Effect of Lifetime to the steel demand with Larger turbines

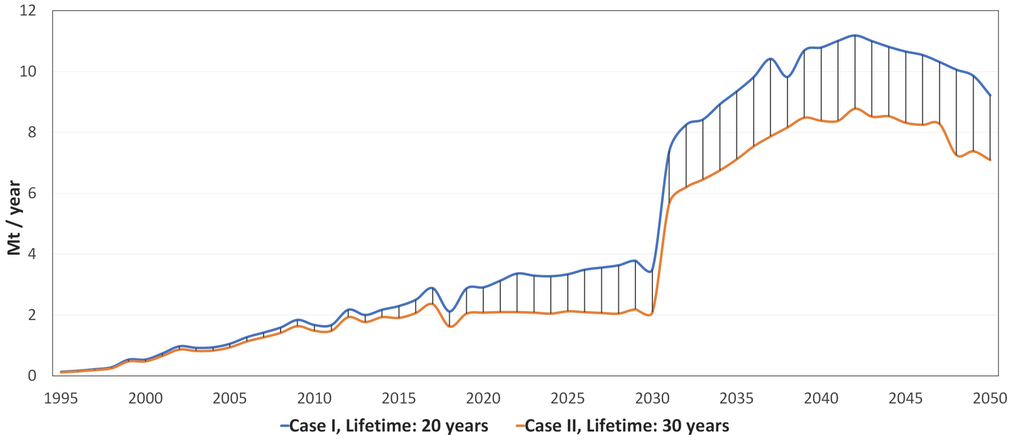
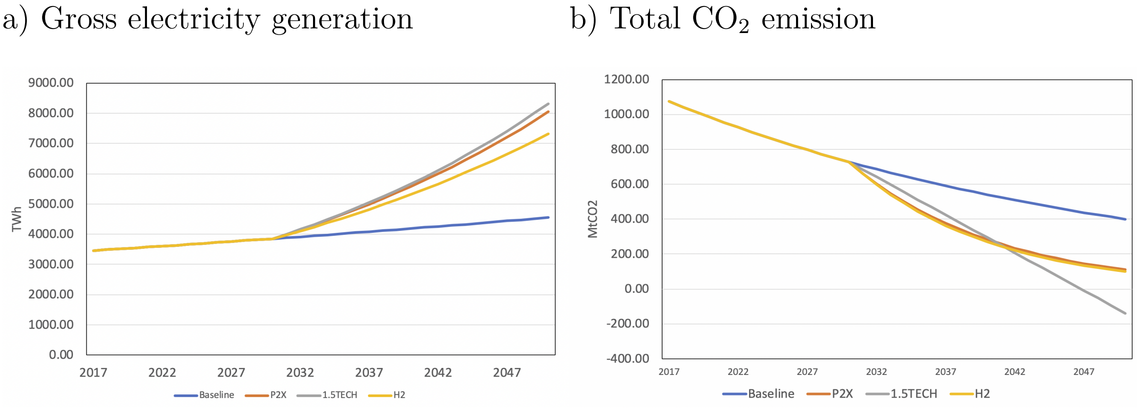


Figure 23: Steel use in two extreme cases

4.3 Emission factor results of the power sector

In this section, the estimated results from the power sector regarding previously mentioned in the Methodology section are displayed. According to the Figure 24-25, the emission factor of the electricity generation in a unit of kg CO_2/kWh was computed corresponding to the total electricity generation and total CO_2 emission from the power sector (Figure 24). The emission factor results of the grid are presented in Figure 25. The results show that higher penetration of renewable energy contributes to lower emission factor of the electricity generation and even reaches the negative emission factor in 1.5TECH scenario.


a) Gross electricity generation

b) Total CO_2 emission

Figure 24: Projection of gross electricity generation and total CO_2 emission in different scenarios.

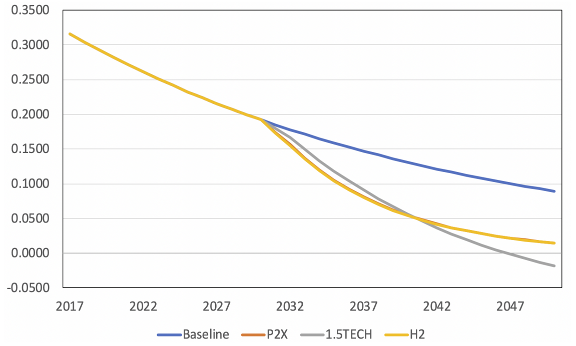
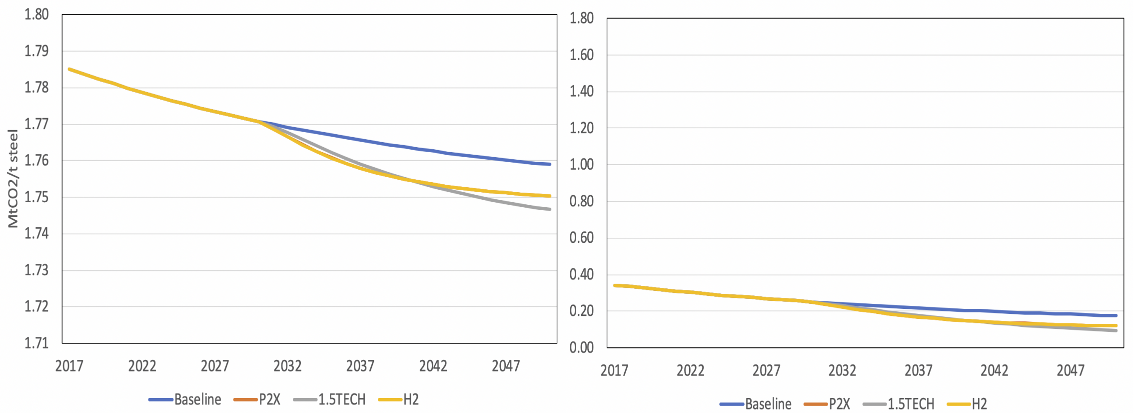


Figure 25: Emission factor of electricity generation based on the total electricity generation and CO_2 emission of the power sector in different scenarios.

4.4 Emission factor results of different steel making technologies



a) BOF

b) EAF

c) DRI/EAF

d) HYBRIT

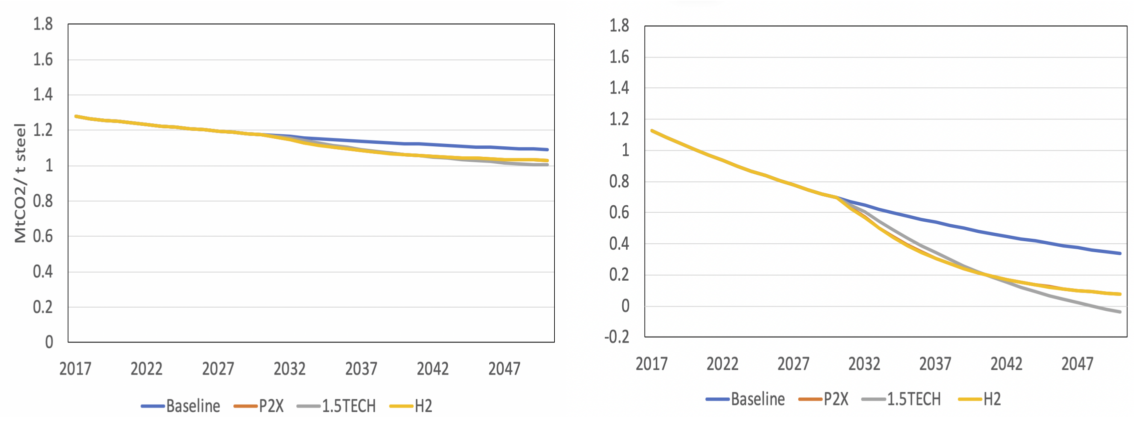


Figure 26: Results of emission factor of steelmaking technology for different scenarios

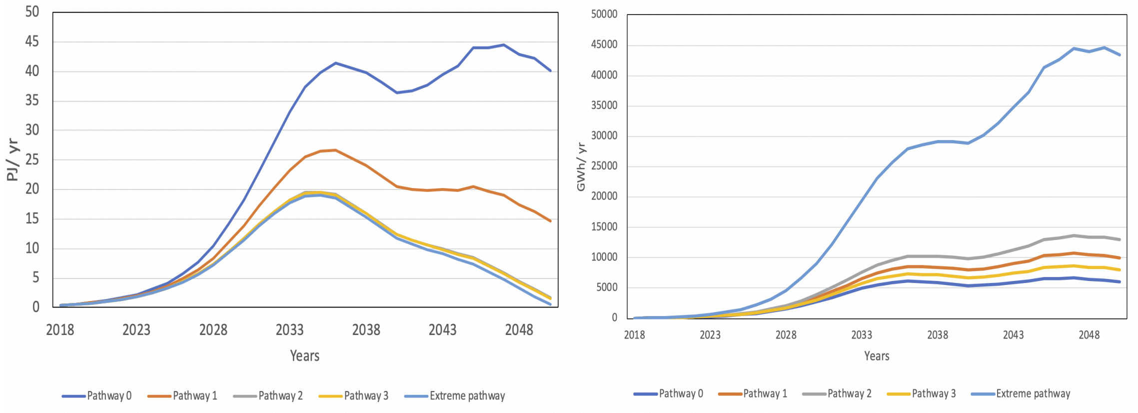
The results are displayed for different steelmaking technologies from Figure 26. Also, the emission factor results reflect that the specific emission of the grid will affect the emission factor of each steel route differently depending on the total electricity consumption for each steel making technology.

4.5 Total primary energy consumption of the steel production

4.5.1 BEV

a) Coal

b) Electricity



c) Natural gas

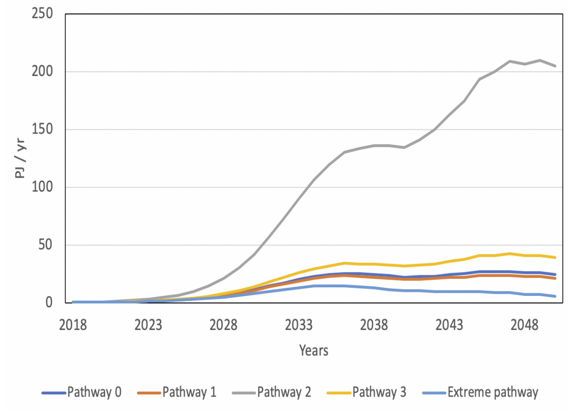
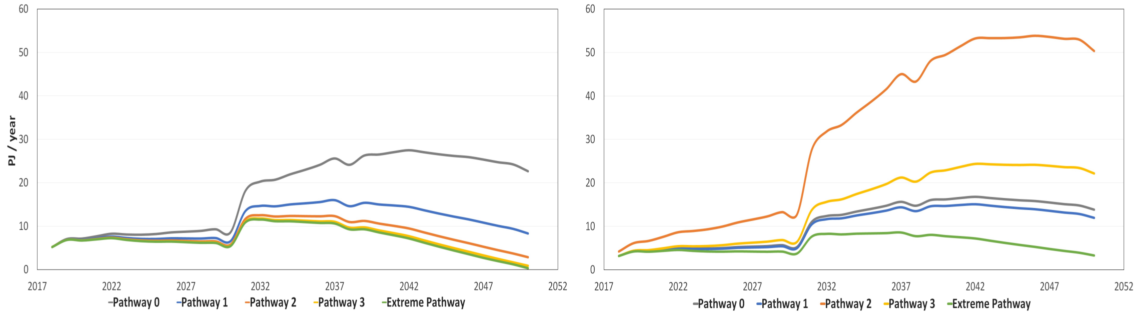


Figure 27: Total primary consumption based on energy carrier for different pathways

In this section, the total primary energy consumption results for the steel production of BEV are presented in Figure 27. The energy used in the steel process is based on various energy carriers for different steelmaking pathways. The electricity consumption is similar for every pathway from 2018 to 2024 but the extreme pathway shows a significant deviation of electricity consumption apart from other pathways.

For the case of coal consumption, pathway 0 and extreme pathway indicate rising of consumption, especially for the extreme pathway, comparing to other pathways.

4.5.2 Wind Energy


a) Coal

b) Natural Gas

c) Electricity

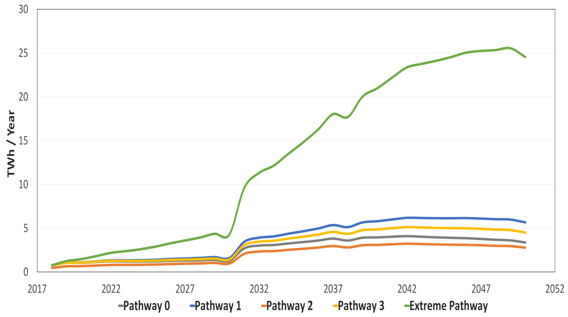
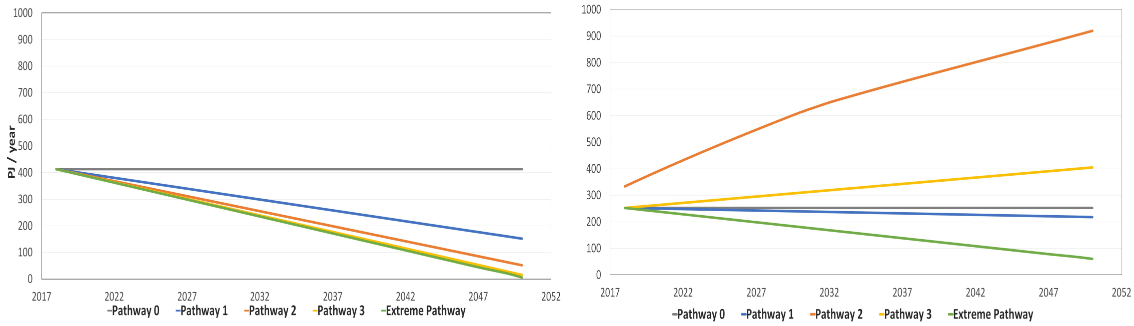


Figure 28: Total primary consumption based on energy carrier for different pathways

Similarly, as the previous section, the total primary energy consumption results for the steel production for Wind power are presented in Figure: 28. The energy used in the steel process is based on various energy carriers for different steelmaking pathways. The consumption energy from a certain type of energy carrier is different in the various pathways because of the varied share of steel making technologies involved in a pathway. The extreme rise in energy usage after 2030 because of the increase in steel demand. In general, it can be seen that energy use rises after 2030 for all the carriers. The energy use from all the carrier is almost similar for each pathway until 2030.

4.5.3 EU steel production



a) Coal

b) Natural Gas

c) Electricity

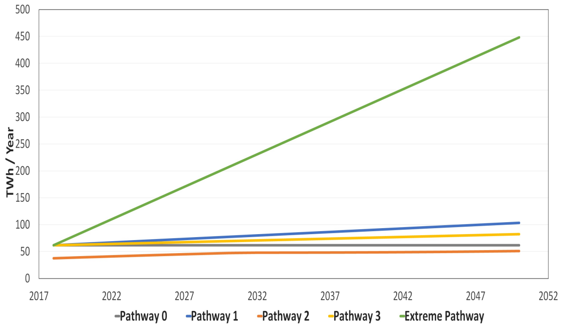
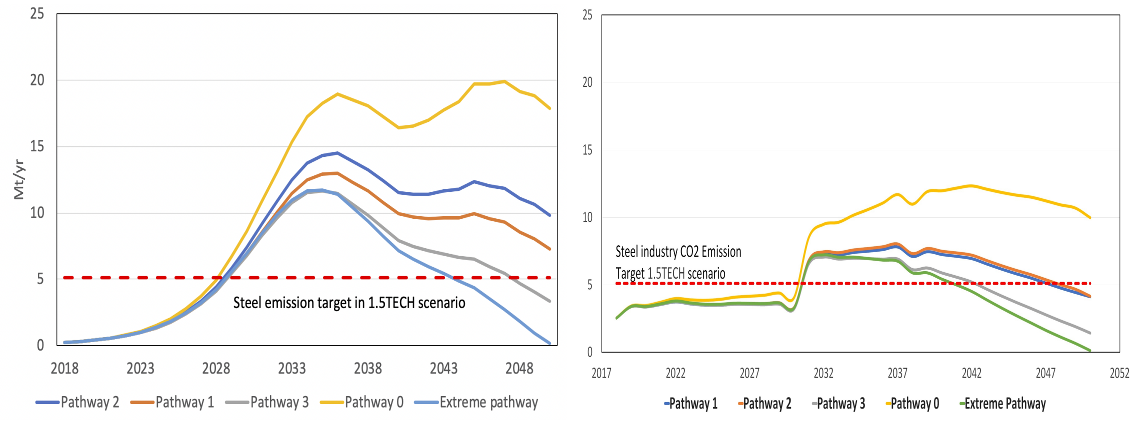


Figure 29: Total primary consumption based on energy carrier for different pathways for EU steel production

The total primary energy consumption from the entire steel industry in the EU are presented in Figure: 29. The energy used in the steel process is based on various energy carriers for different steelmaking pathways. The results are based on the assumption that the annual steel production in the EU from 2008-2050 is same as 2017 i.e, 168.4 Mt. The patterns are similar to wind and BEV among the three energy carries, the coal use in the Pathway 0 is seen to be almost constant. Finally, pathway 2 and extreme pathway marks the increase of Natural gas and electricity use respectively.

4.6 Annual CO_2 emission of the steel production

Regarding an estimation of CO_2 emission from the future steel demands, the CO_2 emissions are explored, and the results will be shown in Figure 30. The results illustrate that the high CO_2 emission will associate with the high steel demands for both wind power and BEV in 1.5TECH scenario. The highest emission occurs in pathway 0, which assuming the steel industry continue to sustain the share of the fossil-based steel technologies for producing the primary steel. However, the potential of future CO_2 reduction appears in the pathway with the zero-carbon technologies and having a high share of secondary steel production, pathway 1, pathway 3 and extreme pathway. Furthermore, the scenarios used for the electricity generation based on renewable energy also affect the CO_2 reduction capacity. For example, 1.5TECH scenario has the lowest emission factor from the grid, which contributes to lower CO_2 emission from EAF and HYBRIT because these two technologies depend on the electricity for the steel production.


a) BEV

b) Wind energy

c) EU steel production

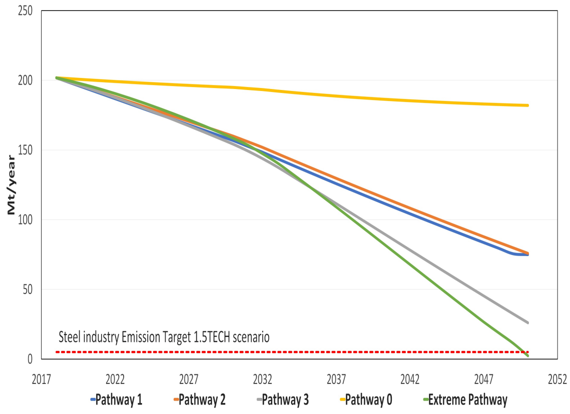


Figure 30: The results of annual GHG emission from the steel production of BEV, wind power and EU steel production, which are compared to the GHG reduction goal in 1.5TECH scenario for the EU steel industry.

According to the result of pathway 2, implementing only DRI/EAF is not sufficient enough to reduce the CO_2 emission down below an emission limit compared to pathway 3 for BEV which having the HYBRIT technology including DRI/EAF. Pathway 1, which has high shares of the secondary steel production, can reduce CO_2 emission drastically compared to pathway 0. Moreover, the extreme pathway shows even better potential results of lower CO_2 emission level from the steel production than pathway 3. The results of CO_2 emission from the steel production are shown in Figure 30for BEV and Wind power.

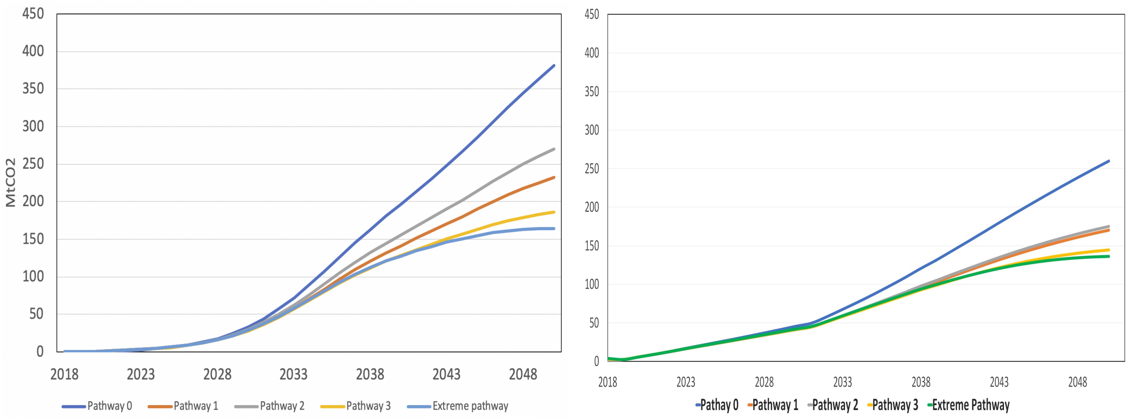
In order to clarify the significant effect of CO_2 emission from the steel production, the results of the CO_2 emissions from various pathways are further compared to emission reduction goals in the steel industry to 95% of 2015 level in 1.5TECH scenario. The reason behind this is to investigate that whether shifting to low-carbon technologies could satisfy the CO_2 reduction goal of EU commission or not. Another reason is an awareness of omitting CO_2 emission from energy generation and transpiration could shift CO_2 emission to the steel industry instead. If the increasing steel demands cause this trend to happen, the benefit from the clean technologies should be reconsidered. The European Commission (2018a) has specified the emission reduction in the scenarios for various industries by 2050. In the case of 1.5TECH the emission reduction in steel industry should be 90% of 2015 level by 2050 which roughly is around 5.1 $MtCO_2$. Looking into the EU steel production level, the CO_2 emission results are still below the CO_2 emission limit level when 1.5TECH scenario is implemented with the extreme pathway of the steel production. However, other pathways seem to be ineffective enough to sustain the CO_2 emission within the emission goal.

4.7 Accumulated CO_2 emission of the steel production

According to consensus of the Paris Agreement to retain the global temperature rise below 2°C degree, various road maps have been developed to mitigate CO_2 in an atmosphere including the global carbon budgets, which limiting total CO_2 accumulated during the considered period. However, only the carbon budgets of the EU will be compared to the results of the CO_2 emission from the new steel demands by wind power and BEV. Therefore, the annual CO_2 emissions from the steel production of each pathway are further aggregated until 2050 in order to compare with the EU carbon budgets. Regarding the study of (Meyer-Ohlendorf et al., 2018), the carbon budgets of EU is left at 50 $GtCO_2eq$ for the 1.5 °C degree scenario and 90 $GtCO_2eq$ for the 2°C degree scenario during the period of 2020 to 2100. The accumulated CO_2 emission results of steel production are shown in Figure31 for BEV, wind energy and EU steel production level. Regarding the EU emission budget, the accumulated CO_2 emission results are around 400 $MtCO_2$ for BEV and 270 $MtCO_2$ for wind energy in 2050, which is far less than the EU emission budget. Furthermore, the accumulated CO_2 result of the extreme pathway shows a significantly lower level than the EU carbon budget. In case of the accumulated CO_2 emission results for EU steel production level, the maximum emission level reaches at approximately 6.319 $GtCO_2$ in 2050 for Pathway 0, accounting as 12.54% and 7.02% of the total EU carbon budgets for 1.5°C and 2°C climate targets respectively.

Table 8: Accumulated CO_2 emission from the steel production for BEV, wind energy and total EU steel production until 2050 in different pathways

Pathway	**EU steel production, $MtCO_2$**	**BEV, $MtCO_2$**	**Wind energy, $MtCO_2$**
Pathway 0	6319	381.66	270.02
Pathway 1	4564	232	174.44
Pathway 2	4659	270	179.24
Pathway 3	4095	186	146.03
Extreme Pathway	3965	164.2	136.35


a) BEV

b) Wind energy

c) EU steel production

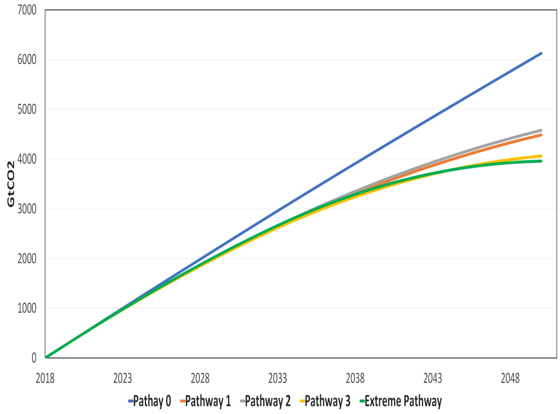


Figure 31: Accumulated CO_2 emission from the steel production for BEV, wind energy and total EU steel production, between 2018-2050.

5

Discussion

5.1 Future steel demand

5.1.1 BEV

The future demands of steel highly depend on the penetration level of BEV and also steel content in the BEV, which indicate the uncertainty. The different population scenarios are less affected to the results of the annual steel demand than the impact of variation of the vehicle lifetime and the steel content in BEV. Regarding the results of various scenarios, it highlights the possible outcomes that could possibly occur depending on the different choice made in the upcoming future. If the material choices are influenced by the lightweight material due to the weight reduction purpose, this will indicate less future steel demands. Therefore, the future steel demands of BEV is highly affected by the steel content in new BEV that will be produced in the upcoming future. Another important parameter is the vehicle lifetime.

The variation results show that the vehicle lifetime highly affected the development of future steel demands. The results indicate that the low vehicle lifetime scenario will require higher amounts of steel annually comparing to the high vehicle lifetime scenario. Also, the low vehicle lifetime scenario requires the additional steel demand due to end-of-life earlier before the high vehicle lifetime scenario. Therefore, the steel demand for ELV will be added up with the steel demand for new BEV. This contributes significant amounts of net steel demand due to BEV production. In contrast, when considering an end-of-life vehicle, there is an opportunity to recycle the steel from the old vehicles. As a result, this helps to avoid a new steel production. As a consequence, the annual steel required for the BEV production will diminish, showing potential for energy and resource saving as well as prevention of CO_2 emission. However, the saving amounts of steel are based on the recycling rate. In addition, the actual lifetime of the vehicle can be influenced by the behaviour of owners regarding vehicle maintenance. Besides, there is the opportunity that BEV owners will use their vehicle less than the average vehicle lifetime. Therefore, these cans fluctuate the vehicle lifetime.

5.1.2 Wind Energy System

As stated in the previous sections the annual steel demand is dependent on the wind capacity growth, size and service life of the turbine. It can be seen that 1.5TECH and P2X scenario has the highest steel demand as this scenario foresees the most wind energy penetration. The average steel demand in the Mechanical Engineering sector approximately 25 Million tonnes in the year 2017 is used as a metric of comparison. In most of the scenarios in Figure: 17 it can be seen that the annual demand rises on and after 2030. The wind capacity growth in Figure: 2 shows that the implementation of the scenario in the EU occur after 2030 and the growth curves of the scenario are steep after 2030. This leads to the higher annual demand of steel between the years 2030-2050. The considered services life of the turbines (offshore & onshore) are 20 years. So after the end of service life, the turbines have to be replaced and the steel demand adds up to the year corresponding. The future annual demand is inclusive of the steel required to build a new turbine as well as the substituted or replaced turbine after the end of service life. Study reports from SIEMENS (2014) and World steel (2012) reveal that after a turbine is dismantled when it reaches End of life, often they are replaced with bigger turbines and the older turbines are refurbished and installed elsewhere. The other way is that most of the metals parts are recycled back and used as reinforced steel in the foundation. Since the tower is built with mostly primary steel not recycled steel. Additionally, recycling leads to the recovery of materials that reduces primary metal extraction.

Additionally, the results presented the Figure: 21 and Figure: 22, it is evident that steel demand annually is lower with higher Lifetime, for both of the cases. The results are presented below in the Figure: 21 and Figure: 22, it is evident that steel demand annually is lower with higher Lifetime, for both of the cases. The geographical aspects which are the wind capacity and steel demand in various EU member states are not considered, the EU is considered as a whole. The lifetime of 20 years and 30 years can be considered as a low and high case in terms of steel usage, and 25 yeas lifetime as the medium case. The steel used in the medium case does not fluctuate much like the high and low for different turbine size. To examine the extremes in other words to see the variations in the lowest and highest steel use for various cases we use the results in Figure: 21 and Figure: 22. From obtained results, we could draw a conclusion that larger turbines with high lifetime consume less steel than smaller turbines with low lifetime. The Figure: 23 shows the two instances from the result where the steel use is highest and lowest. The highest being for the Case 1 (smaller turbine) and 20 years lifetime and lowest being the Case 2 (larger turbine) with 30 years lifetime. So it can be concluded that with the particular assumptions it is always preferable to have a turbine with large capacity and size with a higher life span to reduce the steel demand.

5.2 Primary Energy Consumption on energy carrier and CO_2 emission from steel production

The results of energy consumption by energy carrier indicate that different pathways affect primary consumption based on energy carrier. The pathway having a high share of BOF show the significant primary energy consumption by coal. Similarly, the pathways having a high share of DRI/EAF show a high natural gas consumption. Hence, the energy consumption is dependent on the share of technologies present in a certain pathway. For instance, in the Pathway 0, the share of BOF in primary steel making contributes to about 60% and EAF for secondary steel to 40%, so the energy use in coal as a carrier is significantly higher as most of the steel is produced by BOF. Similarly, the energy consumption level through natural gas in Pathway 0 and 3 is higher due to the growth of DRI technique's in the market. The low prices of natural gas would make the DRI process techno-economically feasible. In order to compensate and divert the energy use towards a more sustainable energy source mainly electricity. The extreme pathway is developed where most of the steel is produced by HYBRIT as steelmaking technology and considering higher scrap availability so that EAF can sustain the secondary steel making. Assuming that the energy system is more dependent on renewables by 2050 and the hydrogen production in HYBRIT technology to produce steel is through electricity produced by biomass with the implementation of BECCS. The use of energy sources which are carbon intensive and fossil-based are reduced more than the present level. As a result, the transition to the zero-emission grid will further decrease the CO_2 emission from the HYBRIT process and even achieve zero emission from the steel production.

The CO_2 results revealed the annual emission level associated with steel demands for both wind power and BEV. The high steel demands directly indicate the high CO_2 emission from steel production. Also, the results suggest that the pathways using fossil-free steelmaking technology and increasing the usage of secondary steel production have the potential to achieve the emission target of the EU steel industry in 2050. This trend also applies to the EU steel production level. However, only the extreme pathway with high penetration of HYBRIT technology in 2050 can sustain the emission level below the emission goal of the EU steel industry. The current steel production mix shared by BOF and EAF will contribute significant amounts of CO_2 emission from the steel production. Considering these findings, the future implementation of steelmaking technology should focus on the development of HYBRIT technology and EAF in order to avoid CO_2 emission from the steel production regarding the wind power and BEV production. However, the capacity of secondary steel production depending on future scrap availability. According to the results of accumulated CO_2 emission, the accumulation levels of CO_2 emission caused by the steel production for BEV and wind energy is notably below the EU carbon budget for every pathway, especially for the extreme pathway. Therefore, the emission from the increasing steel demands of low-carbon technologies will not affect EU carbon budget. However, the CO_2 emission caused by the EU steel production consumes approximately 12% of EU carbon budget in case that the current steelmaking technology mix continues to operate. Furthermore, the CO_2 emission from other EU sectors may be combined together and exceed the carbon budget in the future. These new findings notice an essential transition of the EU steel industry to zero-carbon steelmaking technology. With the study of the transition towards a low-carbon energy system, the most important truth revealed is that only dependency technologies such as BEV and wind energy may be not sufficient for solving climate change. Furthermore, changes have to be made in many sectors such as the transport sector, power sector, and also the steel industry to be more sustainable than the present.

The limitations of the analysis are the specific boundary, parameter assumption and projection of the data used in the study. Furthermore, the implementation of BEV in the market has been very recent so the lack of historical data makes the study difficult to analyse the past growth patterns and to project the penetration of BEV to the future.

6

Conclusion

The study of future steel demands and CO_2 emissions caused by the upcoming transition to low-carbon energy systems by 2050 are conferred in this study based on the European Commission scenario 2018. To answer the first research question reagrding the steel requirement for Wind Energy and BEV, based on their projected capacity increase by 2050, the results depict that the annual steel demand for the production of wind energy and BEV will be around 5-26 Mt until the year 2050. The steel demands depend on the level of penetration of wind power and BEV in the market, even in the most steel intensive 1.5TECH EU scenario, the annual steel demand does not exceed 26 Mt. The conclusion drawn from this result is in the process of decarbonizing the energy system, wind energy and BEV will not be steel intensive as the current EU steel production is around 168 Mt. Thus, the maximum steel demand in any year would be 15% of EU steel production in 2017.

Furthermore, for the second and the third research question concerning the CO_2 emissions, the relative CO_2 emissions from the steelmaking technologies dedicated for BEV and wind energy as well as the electricity generation unitl 2050 were analysed. The emission factor for electricity production is based on the future energy mix which might have lower emission factor due to the high penetration of renewable in the grid by 2050. As a result, the emission factors for fossil-based steel process are higher than the emission factors for electrical-based steel process. The conclusions were drawn from the results of the various steel making technologies mix in different pathways. The results of CO_2 emissions from the steel production for BEV, wind power and EU infer that pathways with higher penetration of technologies such as HYBRIT and EAF can achieve the goal for emission below 5.1 $MtCO_2$ set by EU steel industry in 1.5TECH scenario. Thus, it is suggested that the steel industry should rely more on HYBRIT that is a low-carbon steelmaking technology and the secondary steel production such as EAF to limit the amounts of CO_2 emission from the steel industry below the goal of GHG emission by 2050.

The final conclusion can be made by comparing the cumulative emission from the steelmaking pathways dedicated for the steel demand in BEV and wind energy as well as EU steel production until 2050 with the EU carbon budget for a time-frame of 2020-2100. The result indicates that if the share of steelmaking technology is same as the present (60% BOF & 30% EAF) until 2050, the CO_2 emissions would be around 0.64 Gt of CO_2 from steel production for wind and BEV. With the current rate of steel production 168 Mt in the EU until 2050, the emission would be around 6.319 Gt of CO_2 until 2050. This emission of 6.319 Gt CO_2 from the entire steel industry with the current EU production level may account for approximately 13% of EU carbon budget. Even with this minimal share of emission in the carbon budget the steel industry still has to go through a great transformation towards climate neutral and fossil free steel making to achieve the ambitious steel industry goals (95% emission reduction compared to 2015) by the next three decade. Hence it implies a necessary change for the EU steel industry to a more sustainable steel production and circular economy, relying more on recycled steel and reducing steel production.

Future Scope The higher penetration of wind energy and BEV implies increasing demands of bulk materials and rare earth metals. The further possible scope would be to study and quantify the demand of these materials (i.e., aluminium and cement for bulk material and lithium for critical material) along with their impact towards the environment. An additional scope, the availability of the rare earth metals could be the investigated. The availability might be impacted by material supply due to techno-economic, trade and geopolitical issues. This would also bring out the potential to study alternative materials based on their feasibility of the supply capability and environmental impact.

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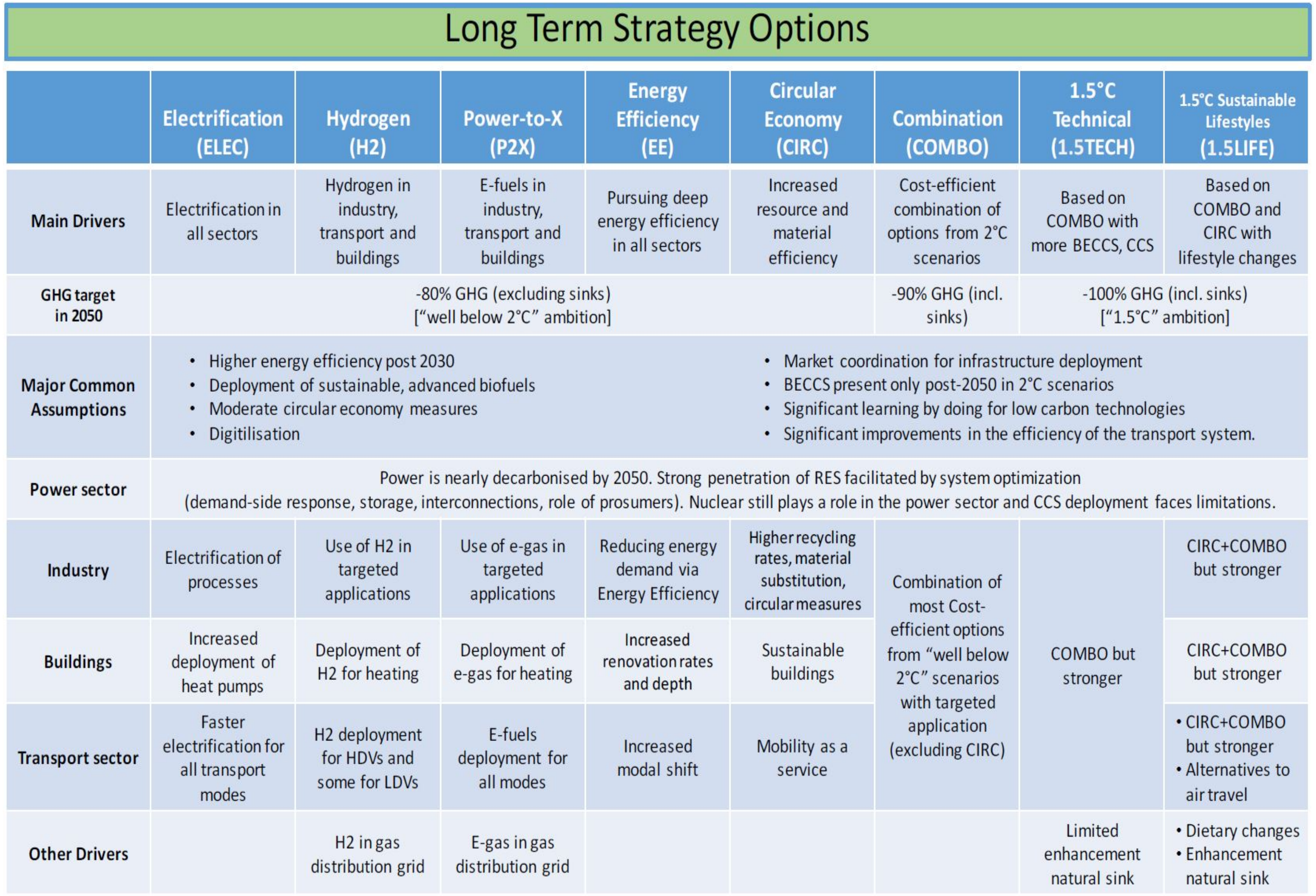
Appendix

Figure 32: Overview of the scenario



Long Term Strategy Options

	Electrification (ELEC)	Hydrogen (H2)	Power-to-X (P2X)	Energy Efficiency (EE)	Circular Economy (CIRC)	Combination (COMBO)	1.5°C Technical (1.5TECH)	1.5°C Sustainable Lifestyles (1.5LIFE)
Main Drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry, transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	-80% GHG (excluding sinks) ["well below 2°C" ambition]					-90% GHG (incl. sinks)	-100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	• Higher energy efficiency post 2030 • Deployment of sustainable, advanced biofuels • Moderate circular economy measures • Digitilisation				• Market coordination for infrastructure deployment • BECCS present only post-2050 in 2°C scenarios • Significant learning by doing for low carbon technologies • Significant improvements in the efficiency of the transport system.			
Power sector	Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher recycling rates, material substitution, circular measures	Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC)	COMBO but stronger	CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 for heating	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings			CIRC+COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDVs and some for LDVs	E-fuels deployment for all modes	Increased modal shift	Mobility as a service			• CIRC+COMBO but stronger • Alternatives to air travel
Other Drivers		H2 in gas distribution grid	E-gas in gas distribution grid				Limited enhancement natural sink	• Dietary changes • Enhancement natural sink