Assessment of Bioenergy as a CO_2 Emission Reduction Strategy for European Iron and Steelmaking

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"It always seems impossible until it's done."

Nelson Mandela

Declaration of authorship

The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated within the text. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Signed: ____________________________

Date: ____________________________

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Abstract

Within the EU, primary steelmaking via Blast Furnace-Basic Oxygen Furnace (BF-BOF) route takes place across 30 integrated steel plants. Such process is highly energy and emission intensive, which classifies these plants as one of the largest single-point CO_2 emitters and puts them under high pressure for significant decarbonisation. A potential strategy for instant emission reduction is partial-substitution of coal-based fuels, used in the process, by bio-based fuels.

The aim of this project is to assess whether the use of limited biomass resources for this purpose is a strategic decision for the European iron and steel industry and identify barriers hindering such fuel switching. Using sophisticated techno-economic models, this work identifies the potential CO_2 emission savings, compares opportunities for biomass deployment across the individual plants and defines the required carbon price to enhance its economic viability. The results show bioenergy can reduce up to 40 % of on-site CO_2 emissions in total, where any further reduction is limited by the technical viability rather than biomass availability. However, bioenergy emission reduction potential could be further enhanced by its deployment with CCS (as bio-CCS). As the bio-CCS technology depends on biomass as well as CCS aspects, plants which present prominent opportunities for biomass integration are not necessarily the plants that stand out for the bio-CCS deployment and vice versa.

In general, plants in France present an outstanding opportunities for biomass, followed by plants in Sweden and Finland. Overall, bioenergy use in European iron and steel plants could help to meet the industry's CO_2 emission targets set for the near future, but other technologies or its deployment with CCS would be necessary to meet the strict targets set for 2050.

Publications

Journal articles

H. Mandova, P. Patrizio, S. Leduc, J. Kjärstad, C. Wang, E. Wetterlund, F. Kraxner, W. Gale. 2019. Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage. *Journal of Cleaner Production* **218**, 118-129.

H. Mandova, S. Leduc, C. Wang, E. Wetterlund, P. Patrizio, W. Gale, F. Kraxner. 2018. Possibilities for CO_2 emission reduction using biomass in European integrated steel plants. *Biomass and Bioenergy* **115**, 231-243.

H. Mandova, W. Gale, A. Williams, A. Heyes, P. Hodgson, K. Miah. 2018. Global assessment of biomass suitability for ironmaking - Opportunities for co-location of sustainable biomass, iron and steel production and supportive policies. *Sustainable Energy Technologies and Assessments* **27**, 23-39.

Conference papers

H. Mandova, P. Patrizio, S. Leduc, J. Kjärstad, C. Wang, E. Wetterlund, F. Kraxner, W. Gale. 2018. Modelling bio-CCS deployment across iron and steel plants in Europe. Paper presented at the *14th International Conference on Greenhouse Gas Control Technologies (GHGT-14)*, Melbourne, Australia. Available at SSRN: https://ssrn.com/abstract=3366034

H. Mandova, W. Gale, A. Williams, A. Heyes. 2018. Blast Furnace Emission Reduction Potential by Charcoal Injection. Paper presented at the *26th European Biomass Conference and Exhibition (EUBCE)*, Copenhagen, Denmark. 1353-1358.

Abbreviations

ar	As received
BATs	Best available techniques
Bio-CCS	Bioenergy with Carbon Capture and Storage
BF-BOF	Blast Furnace-Basic Oxygen Furnace
BF-TGR	Blast furnace with top gas recycling
CCS/CCUS	Carbon Capture Utilisation and Storage
CMIP5	Coupled Model Intercomparison Project phase 5
CS	Crude steel
CSI	Coke reactivity index
CSR	Coke strength after reaction
daf	Dry ash free
db	Dry basis
DRI-EAF	Direct Reduced Iron- Electric Arc Furnace
EU-ETS	European Union Emission Trading System
EOR	Enhanced Oil Recovery
EUROFER	European Steel Association
GSI	Global Suitability Index
HSI	Habitat Suitability Index
HM	Hot metal
HRC	Hot rolled coil
IEA	International Energy Agency
IIASA	International Institute for Applied System Analysis
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	IPCC Fifth Assessment Report
IPCC SR15	IPCC Special Report on Global Warming of 1.5C
LSI	Land Suitability Index
NIPALS	Nonlinear iterative partial least squares
PCA	Principal component analysis
PCI	Pulverised coal injection
ULCOS	Ultra-Low CO_2 Steelmaking
UNFCCC	United Nations Framework Convention on Climate Change

Nomenclature

Parameters

$d_p^{CokingCoal}$	Demand for coking coal by an integrated steel plant p
d_p^{Coke}	Demand for coke by an integrated steel plant p
d_p^{PCI}	Demand for PCI by an integrated steel plant p
$\bar{e}_{r,p}^{present}$	Amount of CO_2 emissions currently produced by integrated steel plant p in region r
$e_r^{ByProducts}$	Emissions allocated to the by-products production generated during cokemaking at region r
$e_r^{CokingCoal}$	Emission intensity of coking coal at region r
e_r^{Coke}	Emission intensity of coke at region r
e_r^{PCI}	Emission intensity of PCI at region r
H	Number of different harbours for inter-EU trade considered
$\widetilde{H}$	Set of different harbours
M	Number of different types of raw materials considered
$\widetilde{M}$	Set of raw materials
o_a	Multiplication factor representing the additional amount of CO_2 due to increased energy demand resulting from the deployment of CCS
P	Number of integrated steel plants considered
$\widetilde{P}$	Set of integrated steel plants
$p_r^{ByProducts}$	Price of by-products at region r generated during cokemaking
$p_r^{CokingCoal}$	Price of coking coal at region r
p_r^{Coke}	Price of coke at region r
p_r^{PCI}	Price of PCI at region r
$p_{r,a}^{CO2capture}$	Price of CO_2 capture for integrated steel plants in region r using capture technology a
$p_{r,p}^{CO2Transport}$	Price of CO_2 transport for an integrated steel plant p in region r
$p_{r,p}^{CO2Storage}$	Price of CO_2 storage for an integrated steel plant p in region r

R	Number of different regions considered
$\widetilde{R}$	Set of different regions
S	Number of supply locations
$\widetilde{S}$	Set of supply locations
T	Number of upgrading technologies
$\widetilde{T}$	Set of upgrading technologies
w_t	Calibration taking into consideration lower quality fuels produced from technology t
$\bar{x}_{p,t}$	Restriction on the amount of bio-product, produced using upgrading technology t, that could be used within an integrated steel plant p
Y	Number of bio-products
$\widetilde{Y}$	Set of bio-products
z	Carbon tax imposed on CO_2 emissions produced across the integrated steel plant
$\eta_{p,t,y}$	Conversion efficiency for producing bio-product y using technology t at plant p
γ_a	Capture efficiency for technology a

Variables

$b^{domestic}_{s,m,p,t}$	Amount of biomass of type m delivered from supply point s to plant p to be used by technology t
$b^{imported}_{h,m,p,t}$	Amount of biomass of type m, produced within the EU, delivered from harbour h to plant p to be used by technology t
$b^{nonEU}_{h,m,p,t}$	Amount of biomass of type m, produced outside of the EU, delivered from harbour h to plant p to be used by technology t
$c^{FossilSteel}_r$	Cost of fossil fuels used by an integrated steel plants at region r
$c^{CO2capture}_r$	Cost of CO_2 capture from integrated steel plants at region r
$c^{CO2Transport}_r$	Cost of CO_2 transport from integrated steel plants at region r
$c^{CO2Storage}_r$	Cost of CO_2 storage from integrated steel plants at region r
$e^{FossilSteel}_r$	Emissions from fossil fuels used at integrated steel plants in region r
$e^{CCS}_{r,p}$	Emissions captured via CCS at an integrated steel plant p in region r
$f^{CokingCoal}_p$	Amount of fossil-based coking coal used at plant p
f^{Coke}_p	Amount of fossil-based coke used at plant p
f^{PCI}_p	Amount of fossil-based PCI used at plant p

$k_{p,a}$	Binary variable indicating whether integrated steel plant p has capture technology a deployed
$u_{p,t}$	Binary variable indicating whether integrated steel plant p is using biomass produced by technology t
v_p	Binary variable indicating whether bio-products will be substituting coking coal or coke
$x_{p,t,y}^{CokingCoal}$	Amount of bio-coking coal type y used at integrated steel plant p, produced using technology t
$x_{p,t,y}^{Coke}$	Amount of bio-coke type y used at integrated steel plant p, produced using technology t
$x_{p,t,y}^{PCI}$	Amount of bio-PCI type y used at integrated steel plant p, produced using technology t

Subscripts

a	CO_2 capture technology number
h	Harbour number
p	Integrated steel plant number
r	Region number
s	Supply point number
t	Upgrading technology number
y	Bio-product number

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Chapter 1

Introduction

1.1 Steel industry contribution to global warming

Ambient temperature data has been available since the 1860s, via the modern record keeping properly since 1880 [157]. The collected data over the time indicate that global warming, i.e., the estimated increase in the global mean surface temperature, has been accelerating since 1990 [4], as shown in Figure 1.1. Global warming is influenced by both, Earth's natural cycles as well as human activities, but the natural causes are too small to provoke the recent rapid changes [128]. As of 2018, the anthropogenic global warming has reached approximately 1.0°C, and currently increasing at a rate of 0.2°C per decade [112]. The process of global warming and the corresponding climate-related risks for humans, animals and whole ecosystems (in a form of increased incidences of extreme temperatures, severe storms, sea level rise, etc.) are broadly addressed as climate change.

First mention of climate change in the global policy agenda has been in 1992, when an international environmental treaty called the United Nations Framework Convention on Climate Change (UNFCCC) first defined a structure to prevent dangerous anthropogenic interference [220]. This was then taken seriously in 1997 by Kyoto Protocol, which legally bound developed country parties to emission reduction targets [221]. In 2009, the Copenhagen summit defined the goal to reduce greenhouse gas (GHG) emissions such that global temperature rise does not exceed 2°C [222]. This effort was then pushed even further in Paris in 2015, which stressed the necessity to keep the temperature rise well below 2°C by the end of the century and pursue a rise of no more than 1.5°C [225]. However, the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR15) published in 2018 [112] stressed that a temperature rise of 2°C will have irreversible impacts on the nature and meeting 1.5°C is hence necessary [112].

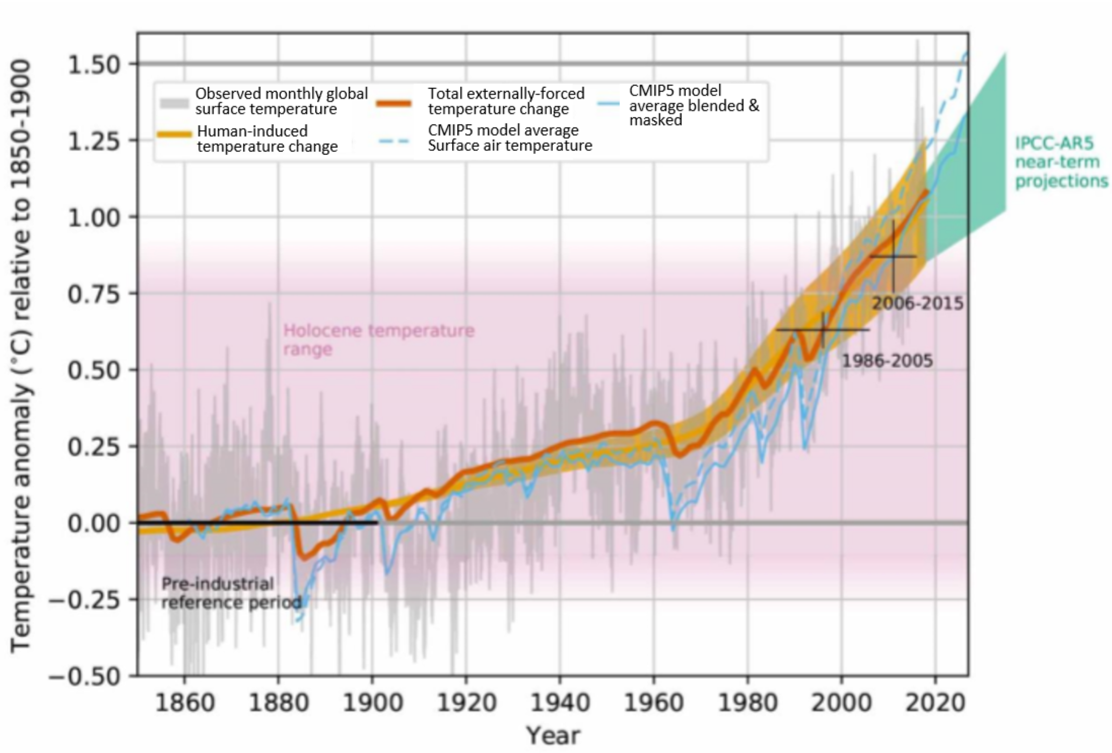


Figure 1.1: Increase in the global mean surface temperature from pre-industrial reference period up to today. Grey line represents real data observations, which are influenced by the human- and naturally-forced contributions represented in red. The range of human specific contribution, considering also the uncertainty, is demonstrated in yellow. Blue lines represent the modelled results from CMIP5 (Coupled Model Intercomparison Project phase 5) for air temperature only (dashed) as well as blended surface air and sea surface temperature (solid). Temperature range experienced during the whole Holocene is shaded in pink. Near term predictions for increase in the average global mean surface temperature given by the IPCC Fifth Assessment Report (IPCC AR5) are highlighted in green. Figure taken from the IPCC SR15 [4].

The difference between 1.5°C and 2°C global warming target in terms of the corresponding impacts and risks is large. The IPCC Third Assessment Report [110], published in 2001, first identified the five integrative reasons for concern (often referred to as RFCs) of the implications resulting from the raise of the global mean surface temperature. The concerns include destruction of unique and threatened systems, increase in extreme weather occasions, uneven distribution of impacts, loss of ecosystems and diversity as well as occurrence of large scale singular irreversible events [112]. Figure 1.2 demonstrates the difference in risks of each, as the global mean surface temperature increases. In detail, the 0.5°C difference presents higher risk of having droughts and precipitation deficits for some areas, whilst other areas will struggle with heavy flooding. The approximate 100mm

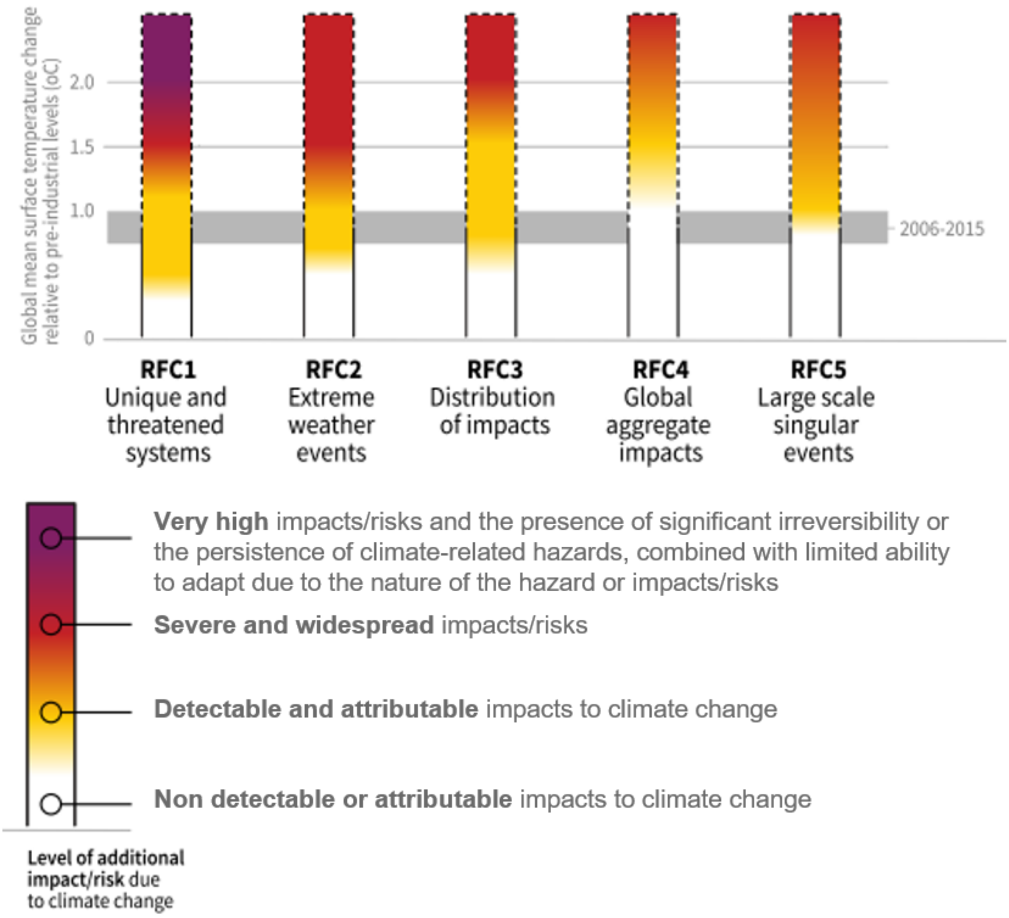


Figure 1.2: Risks related to climate change expressed via the five integrative reasons for concern. Figure modified from the IPCC SR15 [4].

increase in the global mean sea level for 2°C, in comparison to 1.5°C, means exposing an additional 10 million people to the related risks [112]. The 2°C of global warming in comparison to 1.5°C would further damage the biodiversity and ecosystems, resulting in species loss and extinction. Significant increase in risk would be also within oceans due to an additional growth of the ocean temperature and acidity, whilst ocean oxygen levels would even further decrease. This would then straight away impact marine biodiversity, ecosystems and fisheries.

Even though global warming is caused by a range of emissions, the focus is generally on carbon dioxide (CO_2) and the remaining carbon budget estimated for each global warming target. Specifically, the term carbon budget refers to the maximum amount of cumulative CO_2 emissions that could be emitted from all anthropogenic sources, in a particular period of time and across a specific region [188]. In this context, for a time period between now and 2100, across the whole world. For reaching 1.5°C degree target, the IPCC SR15 [112] gave a remaining carbon budget estimate of maximum 580 Gt_{CO_2}. Currently, depletion of the total carbon budget is at a rate 42 ± 3 $Gt_{CO_2}year^{-1}$ [112]. To achieve the targeted global warming temperature, significant reduction of production of net global greenhouse gas emissions potentially accompanied with anthropogenic removal of emissions is required [111]. Specifically to meet the 1.5°C target, the IPCC SR15 [112] states that the global net anthropogenic CO_2 emissions have to decline by about 45 % by 2030 from 2010 levels, and reach net zero around 2050. For limiting global warming to below 2°C, CO_2 emissions have to decline by about 20 % by 2030, in comparison to 2010, and reach net zero around 2075 [112].

Such drastic emission reductions in a short period of time require contribution from all sectors, including industry. In 2016, industry produced 8.3 Gt_{CO_2}, which accounted to 24 % of global emissions. Direct industrial CO_2 emissions have been growing every year by an average of 1.3 %, from 2010 to 2016 [103]. For meeting the 2°C target, industry has to reduce its CO_2 emissions by about 50–80 % in 2050 relative to 2010. For the 1.5°C, the required reduction is even higher, 75–90 % [112]. The IPCC SR15 [112] stresses that such emission reduction would, apart from the need to increase energy and process efficiency, also require deployment of new technologies and practices. This includes electrification, hydrogen, sustainable bio-based feedstocks, product substitution, and carbon capture, utilization and storage (CCUS). However, their deployment is currently limited by various economic, financial, technical, human capacity and/or institutional constraints.

The largest industrial CO_2 emitter is iron and steel sector [177]. On its own, the sector accounts for 7 % of the total energy-related CO_2 emissions, which is expected to increase up to 10 % by 2050, based on the International Energy Agency (IEA) 2°C scenario [100]. Iron and steel is also the second-largest industrial energy consumer, after a chemical and petrochemical sector, consuming 23 % of the industry final energy demand [177]. The high emission intensity is due to the primary steelmaking methods, which are responsible for 90 % of the direct CO_2 emissions from the steel industry. An average global emission intensity of crude steel (CS) production is currently around 1.8 $t_{CO_2}{t_{CS}}^{-1}$[249], however the carbon footprint of a specific steel product greatly varies based on the deployed production route. In 2016, the world steel production equalled to over 1.6 billion tonnes of crude steel [252], which averages to around 215 kg of steel use per capita worldwide [249]. Globally, 74 % of crude steel is produced via Blast Furnace-Basic Oxygen Furnace (BF-BOF) route [252], which uses virgin raw materials such as iron ore, coal and limestone. The rest is produced mainly from remelting steel scrap at mini-mills via electric arc furnaces (EAF). Production of steel via BF-BOF route is over two times more emission intensive than via EAF [11], to which power is generally supplied by fossil fuels. In the case of low-carbon electricity source, the magnitude of the emission intensity of BF-BOF route versus EAF route would be even higher. However, the current steel demand makes primary steel production crucial. By 2050, it is expected that the demand for steel will double in comparison to current levels, which emphasises the role of steel production via BF-BOF route in the future as well [175].

Steel is a globally traded commodity and the amount produced either via BF-BOF or EAF route within each country depends on various factors (e.g., availability of natural resources, labour cost, economic growth). In general, steel production via EAF route is much more distributed across countries than via BF-BOF route, to which China heavily dominates [252]. The reason for so is that EAF requires lower capital investment, presents easier scalability and most countries already have an easy access to scrap steel. Figure 1.3 shows that steel production across the 28 countries within the European Union (EU) have an important share on the global steel supply via both routes. In detail, the EU-28 countries together are the second biggest producers of iron and steel via BF-BOF route. At the same time, the EU-28 countries are world leaders in steel production via the EAF route. The EU – as a union of developed countries and one of the key world steel producing players – is hence obligated to deploy means to significantly decarbonise its iron and steel industry and be an example that the iron and steel industries in other countries can follow.

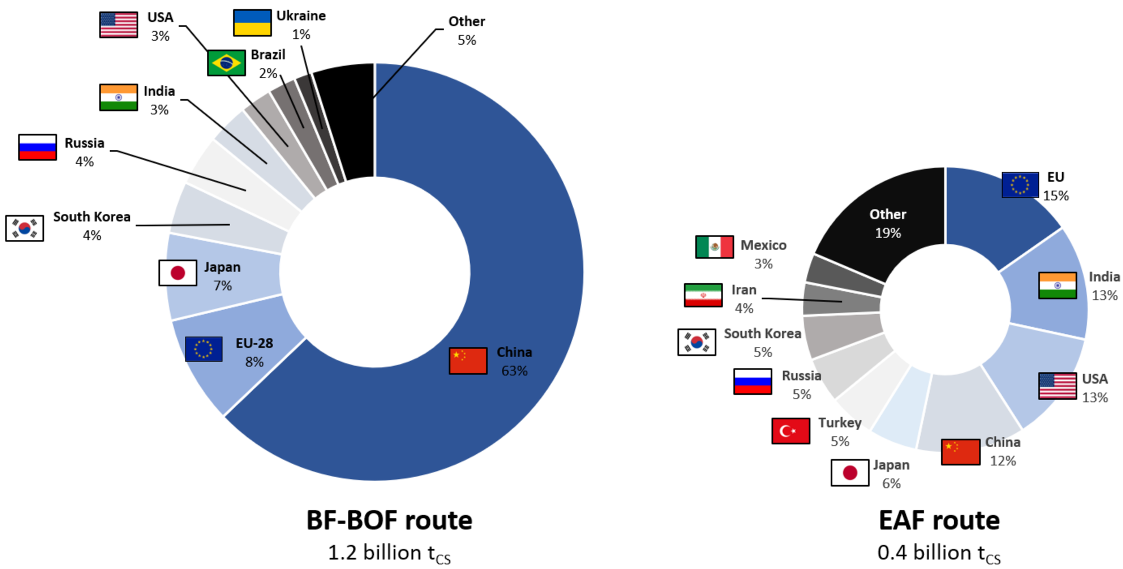


Figure 1.3: Steel production via BF-BOF and EAF route around the world. 2016 data published by the World Steel Association [252]. Note: Steel production from Taiwan and China are considered separately.

1.2 Status of iron and steelmaking in the EU

The European iron and steel industry annually generates over 200 Mt_{CO_2} [19], which amounts to 5 % of all CO_2 emissions produced across the EU-28 countries in 2016 [60]. The steel production within the EU is also dominated by the BF-BOF route, employed at integrated steel plants. In 2016, the 30 operating plants produced 98 million tonne of crude steel (60 % of all the steel produced across the EU) [252]. Steel coming from those plants is of higher quality than steel from recycled scrap, which final steel properties are often negatively impacted by the high amount of impurities [47]. The largest number of integrated steel plants is operating in Germany, which makes it also the biggest steel producing country via the BF-BOF route in the EU. Figure 1.4 shows the distribution of the 30 integrated steel plants and countries share in the total steel production amount via BF-BOF route within the EU.

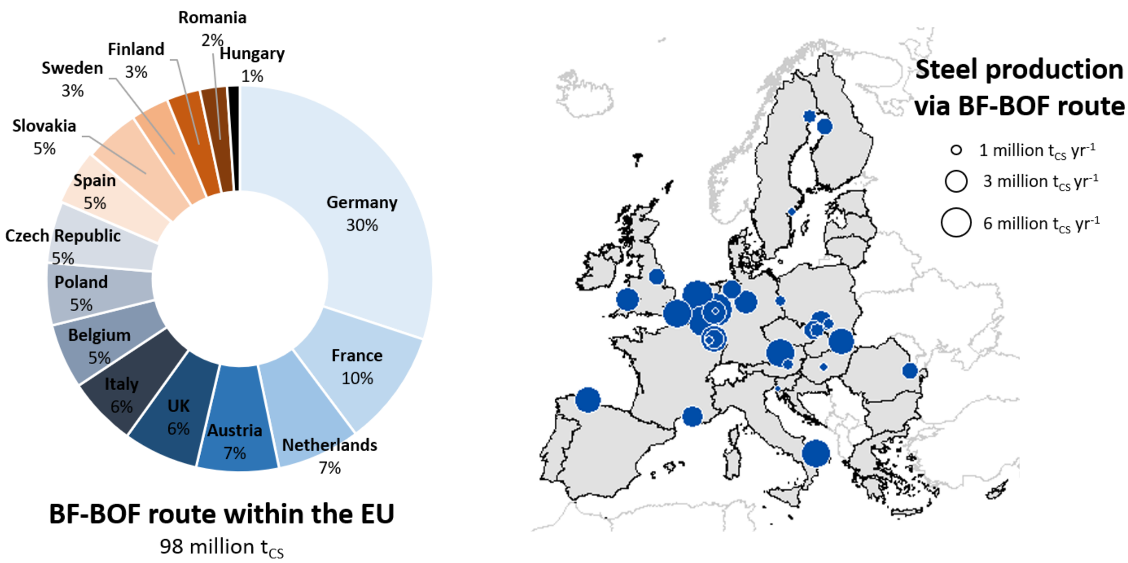


Figure 1.4: Status of steel production via BF-BOF route in the EU and location of the 30 integrated steel plants currently operating. 2016 data published by the World Steel Association [252].

The iron and steel sector is one of the key industries, which CO_2 reduction is essential to meet the EU 2050 greenhouse gas emission targets. Overall across the whole industry sector, the European Commission [52] is aiming to reduce CO_2 emissions by 34–40 % in 2030 and by 83–87 % in 2050, in comparison to 1990 levels. Over the past fifty years, various improvements across the process have already halved the coke consumption, as shown in Figure 1.5 and the European integrated steel plants are operating close to the technical limits. Over the past years, the industry has also managed to offset additional

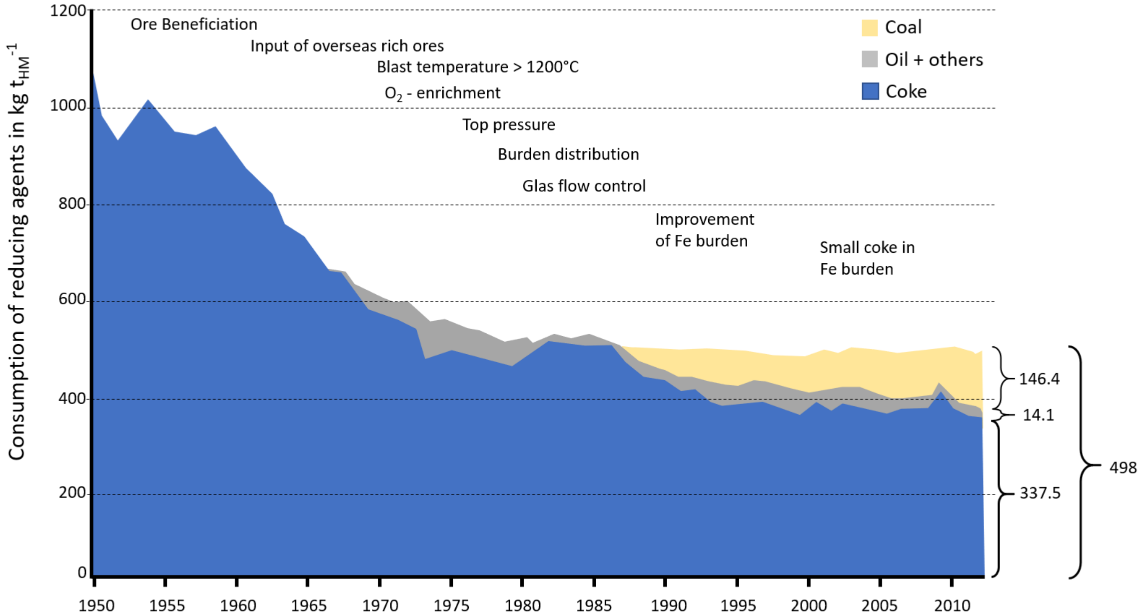


Figure 1.5: Reduction in the consumption of reducing agents in the blast furnaces in Germany as a result of deployment of new technologies over the past 60 years [47].

CO_2 emissions by recovering the waste gases for heat and electricity production, or by further using slags in the cement and construction sectors [47]. Therefore, the targeted reduction of the emission intensity is not economically feasible for the iron and steel industry. The European Steel Association (EUROFER) states that, in the best case scenario, the sector can reduce a maximum 15 % of CO_2 emissions over the next 30 years by the deployment of cost-effective technologies [47].

Deployment of cost-effective technologies is particularly challenging for the iron and steel, as it is one of the least profitable manufacturing industries [25]. In detail, the EU's steel industry is already facing challenges related to the cost and availability of raw materials as well as high competition from non-EU producers [54]. Achieving the set 2050 targets would further undermine the European steel production competitiveness domestically as well as around the world. At the same time, steel is an irreplaceable material for most of the products whose deployment is crucial for meeting the 2050 emission reduction targets in other sectors. The EUROFER has hence argued that steel is actually a CO_2 mitigation enabler and policies must therefore first recognise the contribution that steel material brings to fight against climate change, after focusing on the inevitable emissions resulting from the material production [47]. Since 2005, the iron and steel has been allocated emission allowances under the EU Emission Trading System (ETS). However, after 2020, the capping of emission allowances will increase from 1.74 % to 2.2 % per year [58].

An ECOFYS study by Borkent & Beer [19] point out that the steel industry is going to face an average 38 % annual shortage of those allowances, resulting in total cost of about € 27.1 billion between the period 2021–2030. In May 2017, 76 European steel industry CEOs have raised high concerns that the current EU strategy is non survivable for the industry [48] and that the additional costs would make European steel plants uncompetitive on the global steel market. Reducing steel production in Europe as a result would also negatively impact the 320,000 jobs that the steel industry directly secures [86]. Reallocating steel production outside the EU would also increase a risk of carbon leakage, as steel production outside the EU is known to be sometimes up to 50 % more CO_2 intensive [48]. The European iron and steel industry is hence seeking technology options that would reduce its emission intensity.

1.3 Technologies for significant emission reduction and the role of bioenergy

In 2013, the European Commission published a Joint Research Centre Reference Report, which presents the best available techniques (BAT's) for each unit within an integrated steel plant [183]. However, Pardo & Moya [172] shows that the required emission reduction would not be possible to achieve only with the best available techniques and innovative technologies have to be deployed in the next 10 to 15 years [172]. Currently, the iron and steel industry is betting on progress of various technologies, which either off-set CO_2 after it is emitted or achieve sufficient CO_2 emission reduction by introducing new reduction processes or reducing agents. In detail, one of the biggest hopes for the iron and steel industry that would require only small retrofit of the plants is CCUS [256], with already one commercial scale plant running in Abu Dhabi. The plant produces steel via Direct Reduced Iron-Electric Arc Furnace (DRI-EAF) route, and uses methane as the reducing agent. The captured CO_2 from the plant is transported via pipelines to oil fields, where it is then further used for enhanced oil recovery (EOR) [85]. Unfortunately the deployment of CCUS within European integrated plants like this is currently unappealing for various reasons. First, there are multiple CO_2 production sources across the plant, with different concentrations of CO_2, which make the maximum realistic emission offset limited to only 60 % [106]. Second, deployment of such technology is economically unappealing. Deployment of carbon capture would increase the steel production cost by 18 % [106], whilst also increasing the plant's energy demand, with no benefit for the final steel product. Third, the industry would be also facing multiple challenges occurring off-site of the plant due to the requirement to generate a new CO_2 transport and storage. The deployment of CCUS has been widely discussed particularly in the combination with blast furnace top gas recycling (BF-TGR) technology. Their combination can reduce coal consumption by 25 % [177] and CO_2 emissions by 47 %, whilst increasing the steel production cost by less than 10 % [106]. However, its drawback lies in the requirement for significant reconstruction of the blast furnaces, which would not be possible to be done during the scheduled maintenances for their refits, typically lasting 48 to 72 hours [125]. At the same time, waiting for a scheduled shut-down might be 15-20 years, which an average length of a blast furnace campaign [125].

Since 2004, the EU's research and development of innovative technologies, that would enable strong reduction in CO_2 emissions, is run under the Ultra-Low CO_2 Steelmaking (ULCOS) programme. Apart from the work on the blast furnace with top gas recycling, the project focuses on other promising technologies, such as HIsarna, Ulcored, Ulcowin and Ulcolysis [182]. In detail, HIsarna uses a hot cyclone smelting, where coal and iron ore can be used directly in the blast furnace [149]. Omitting of sintering and coking process, CO_2 emission reduction of 20 % is expected to be achieved. Combining the HIsarna with CCS can reduce the CO_2 emission intensity up to 80 % in total. There is already a pilot plant in Ijmuiden (Netherlands) operating since 2011, however, full deployment requires first a large-scale pilot plant and several years of testing [211]. Ulcored, on the other hand, focuses on improving the direct reduction technologies together with better opportunities for CCUS installations. But the concept is waiting for a pilot scale deployment first [182]. Lastly, there are electrowinning processes known as Ulcowin and Ulcolys. In detail, the iron is produced by direct electrolysis of iron ore, during which no CO_2 emissions are produced [182]. The difference between the two is mainly at the temperature during which the electrolysis happens [177]. So far, the technology is in the laboratory phase and its further development is still uncertain [182].

Hope for significant emissions reduction is also in the research focusing on using hydrogen. Hydrogen reduction would mean switching existing integrated steel plants from BF-BOF route to DRI-EAF route. Within the EU, there are three on-going projects: HYBRIT in Sweden, H2Future in Austria and SALCOS in Germany [2]. Key assumption that would achieve sufficient emission reduction by deployment of this process is that the hydrogen would be produced through electrolysis, using electricity coming from renewables, or from natural gas accompanied with CCUS. Deployment of this route would make EU independent from international coking coal markets, and significantly reduce consumption of one of its most critical materials [55]. Unfortunately, large-scale iron ore reduction using hydrogen is currently facing many challenges, such as ensuring product quality, insufficient hydrogen infrastructure as well as costs. It is estimated that this process will increase the steel production cost by at least 20–30 % [2].

Opportunities to reduce emissions by direct use of renewables are very limited within the integrated steel plants. In general, renewables could generate electricity, which is then used directly for iron and steel production or for the production of hydrogen as a reducing agent. Otto *et al.* [171] estimate that this can achieve CO_2 emission reductions up to 95 % against 1990 levels. However, it is important to point out that only a minor share of electricity within the EU is currently produced from renewables and increasing electricity use across integrated steel plants means increasing the demand for electricity in the first place. Overall, the most feasible option for renewable energy use is via biomass. Biomass, in the form of charcoal, has been already extensively used within mini-blast furnaces in Brazil [212]. Two blast furnaces operating with charcoal can be also found in Argentina [16]. The European blast furnaces are larger than those in South America, which puts greater pressure on the burden. As charcoal has lower compressive strength in comparison to coke, only partial substitution would be technically possible. So even though biomass has been historically used within the iron and steel industry, the modern iron and steelmaking technologies provide limitations for its usage. On the other hand, the innovative technologies, such as HIsarna, have already included charcoal trials during its pilot testing and the BAT's report published by the European Commission also state that "sustainable biomass needs to be seriously considered" [183]. Bioenergy hence provides a very unique and sufficiently unexplored short-term to medium-term emission reduction possibility for the European iron and steel industry and further research is necessary to identify its role between the other CO_2 mitigation alternatives.

1.4 Research overview

1.4.1 Previous research and gap in knowledge

Work previously done on topics related to bioenergy integration within the iron and steel industry could be categorised into two areas raising an attention to:

- the technical performance of the bio-based fuel, and
- the availability of biomass resources.

Research focus has leaned towards the first aspect over the latter and showed promising results particularly for charcoal. For example, bio-coke of sufficient quality could be achieved from charcoal blends up to 5 % during the coking process, where using charcoal of particle size of 125-250µm could even increase the bio-coke cold compressive strength, when compared to the referenced coke [208]. Babich *et al.* [6] also conclude that combustion behaviour of charcoal is comparable, if not better, than of pulverised coal, providing good opportunity for its injection at the bottom part of the blast furnace. Good performance was also observed during charcoal substitution of coke breeze, where fuel blends up to 20 % improved the sinter yield and productivity [170]. Overall, the research progress shows that partial substitution is possible, but the extent depends on the unit and fuel [155]. It is also highly probable that charcoal would be the preferential bio-based fuel for the fossil fuel switching, as its characteristics are the closest to the substituted fossil-based fuels [206]. Further overview of technical studies could be found in other review articles by, for example, Suopajärvi *et al.* [209] or Wei *et al.* [240].

Understanding of the availability of biomass resources, required infrastructure and economic viability for bioenergy deployment within iron and steel industry has a wide range of gaps. The limited global biomass resources rely on such knowledge to prioritise biomass use in applications, where it cannot be substituted by any other energy means [113]. An example of research focusing on the economic viability is in a work done by Feliciano-Bruzual [70], which compared the economic prospect of substituting charcoal for pulverised coal injected at the bottom of the blast furnace across the nine studied countries. The findings estimate a required carbon tax between 47.1 to 198.7 USD ${t_{CO_2}}^{-1}$ (approx. 40 to 170 € ${t_{CO_2}}^{-1}$). But out of the 15 EU countries that produce steel via BF-BOF route, this study included only Germany. Evaluation of bioenergy as an emission reduction strategy within the EU steelmaking should not be based on price estimates for only one country. Particularly as Germany is facing high competition for biomass resources already from other sectors [74], which makes it potentially one of the least suitable countries for bioenergy integration.

The most comprehensive whole-system research focusing on biomass introduction into blast furnaces has been done for Finland. Suopajärvi & Fabritius [205] evaluated the theoretical, techno-ecological and techno-economic potentials of forest chip and identified their excess available for iron and steelmaking applications. In a further work, Suopajärvi *et al.* [207] showed that the CO_2 mitigation cost are dependent on multiple factors, such as the specific reducer it is substituting, the type of bio-product as well as whether by-products resulted from the bio-products productions are further utilised. The estimates by Suopajärvi *et al.* [207] started on 22 € ${t_{CO_2}}^{-1}$ avoided, however, this could reach up to 150 € ${t_{CO_2}}^{-1}$ avoided. On average, the required CO_2 tax would have to be around

50 € $t_{CO_2}^{-1}$, such that the break-even point is reached [205]. Apart from Finland, research interest has been also in biomass application within the Swedish iron and steel industry [241]. For example, Wang *et al.* [237] discussed availability of biomass particularly for the Luleå plant in the North of Sweden. Another study focused on the impact of the iron and steel industry, as a new woody biomass consumer, on the existing market in Sweden and Finland. Its findings point out a probable increase in the price of by-products and harvesting residues, whilst the price of roundwood is expected to be only slightly affected [168]. Finish and Swedish production, however, present less than 6 % of the steel production via BF-BOF route in the EU (using 2016 statistics [252]). Unfortunately, literature that would consider location specific details in regards to bioenergy potential within other EU iron and steelmaking plants is very limited. This presents a large gap in knowledge and potentially missing opportunities for successful biomass deployment. As Suopajärvi *et al.* [210] point out, bioenergy integration into an iron and steelmaking might not be a feasible option for every country, but it is important to fully evaluate its potential as it can start decarbonising the industry today.

Many studies focusing on emission reduction possibilities for iron and steel in the EU completely omitted listing bioenergy as a technology that can contribute to reaching at least the initial emission reduction targets. For example, work by Pardo & Moya [172] analysing the different technology deployment options to improve energy efficiency and CO_2 emission reduction have not considered fossil fuel substitution by biomass at all. Similarly, Fischedick *et al.* [72] focused rather on CCUS, hydrogen direct reduction and iron ore electrolysis, when evaluating innovative steel production technologies. Brunke & Blesl [21], on the other hand, considered bioenergy in their study focusing on assessments of energy conservation potentials for German iron and steel industry, however, the identified high biochar costs and its low energy conservation potential meant biochar has not been listed as one of the promising technologies in the study. Therefore, further research from the whole system perspective is required to fully understand whether European iron and steelmaking should seriously consider bioenergy as an emission reduction strategy and if so, under which circumstances.

1.4.2 Overall research aim and objectives

Partial substitution of fossil fuels by bio-based products presents a unique opportunity to significantly reduce CO_2 emissions across the European integrated steel plants. Simultaneously, it can increase energy security by diverting away from the use of coking coal, listed together with materials such as cobalt or magnesium as one of the 27 critical raw materials for the EU [56]. Its deployment is, however, limited by multiple factors such as biomass availability, fuel cost, specific policy instruments implemented in each country, etc. which may support or limit the long-term sustainability of the solution. Aspects like those raise a question whether biomass adoption within the European iron and steel industry is a right strategy for its decarbonisation and hence should this be supported?

The research aim is to assess suitability of bioenergy utilisation within the European iron and steel industry. Biomass supply and the economic viability of the solution have always been the main concerns related to any biomass deployment. Therefore the first research question is:

1. *Would the European iron and steel plants be able to source the sufficient amount of biomass and how would the fuel switching impact their steel production cost?*

Biomass utilisation across BF-BOF route could achieve only partial substitution of fossil fuels, which classifies bioenergy only as a short/medium-term strategy for the iron and steel industry. As the industry is under large pressure to become carbon-neutral in the next 30 years, short-term strategies have to compliment the long-term strategies to initiate a serious interest in their deployment. This raises the second research question asked when assessing suitability of biomass for the European iron and steel industry:

2. *Does bioenergy have the potential to be also a long-term emission reduction strategy and have an important role in the total decarbonisation of the European iron and steel plants?*

Even if biomass could contribute towards achieving carbon-neutrality across the European iron and steel industry, it is important to have in mind that biomass resources around the world are very limited, which requires their extremely strategic utilisation. Therefore, bioenergy deployment should be pursued preferentially in those countries, which could source the sufficient amount of biomass under economically appealing costs, but which could also maximise the benefit in terms of the non-economic aspects, for example by providing new local employment opportunities. This leads to the final research question:

3. *Which EU countries should seriously consider bioenergy deployment within their iron and steel industry, as it would be a strategic energy-use decision?*

In order to address the overall aim and the research questions, the following research objectives are proposed:

- Optimise the use of available biomass resources in Europe for existing biomass industries and study the impact of new demand from integrated steel plants on the biomass market.
- Impose different levels of carbon price and evaluate its impact on economic viability of biomass use within each individual iron and steel plant.
- Propose CO_2 transport network across EU, such that every integrated steel plant is connected to off-shore CO_2 storage. Based on that, evaluate prospects for combining bioenergy with carbon capture and storage (bio-CCS) for each individual plant.
- Develop methodology to rank countries around the world based on their co-location of sustainable biomass resources, significant iron and steel production and supportive national policies.

Such steps should enhance the understanding of bioenergy prospects within the European iron and steel sector as well as lead to strategic use of the limited biomass resources in general. The work provides a detailed analysis on country as well as plant level.

1.4.3 Thesis structure

The structure of this thesis consists of six chapters, as shown in Figure 1.6. Firstly, the current situation within the iron and steel industry is explained, followed by the list of emission reduction technologies and the role of bioenergy between them. **Chapter 1** also contains a brief overview of the current research and the gap of knowledge. **Chapter 2** then provides theoretical background related to the iron and steelmaking process, such as description of each unit, energy consumption as well as a list of main air pollutants and the measures implemented for their reduction. This chapter also provides a literature review of bioenergy integration possibilities within the BF-BOF route, including overview of the expected opportunities and barriers related to the fuel switching. By the end of this part, the reader should have a sufficient background on the technical aspects related to bioenergy deployment within the iron and steelmaking process.

Chapter 3 then evaluates the availability of resources across the EU by the development of iron and steel module within the existing techno-economic BeWhere model. The obtained results provide an insight into where biomass would be sourced from and the differences in costs of biomass sourcing across the plants. The following **Chapter 4** studies connection of bioenergy with CCS with an aim to maximise the emission reduction potential of the two technologies. The work compares the costs of achieving carbon neutrality

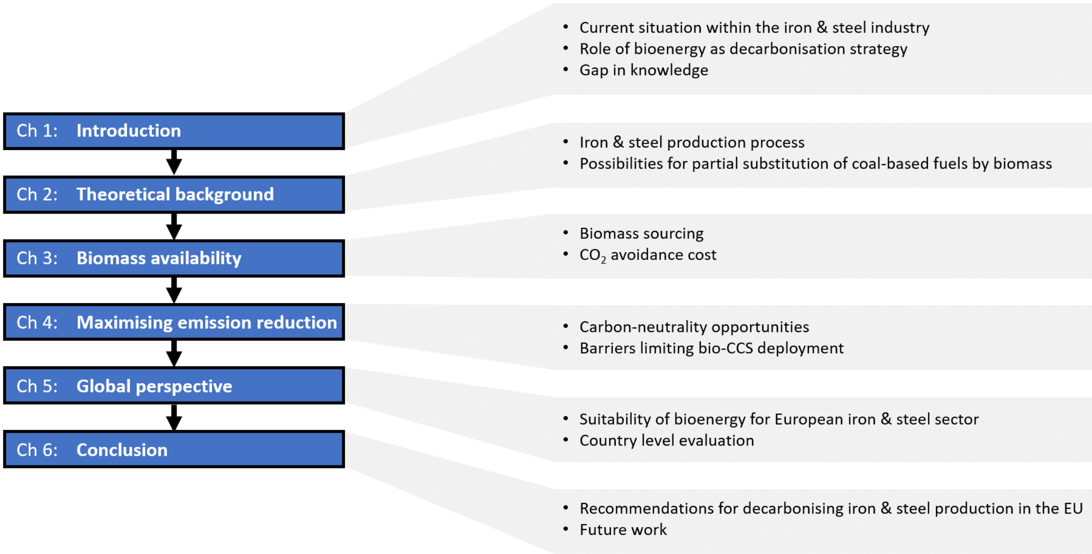


Figure 1.6: Thesis structure and focus points of each chapter.

across all plants and discusses barriers currently limiting the bio-CCS deployment. To obtain a holistic picture whether bioenergy should be deployed within the iron and steel industry in the EU, **Chapter 5** provides a global perspective. By developing the Global Suitability Index, the work completes the analysis by comparing EU countries against the rest of the world and discusses whether biomass use within the European iron and steel industry would be a strategic decision. Lastly, the work is summarised and research aim revisited in **Chapter 6**. This chapter also outlines the contribution to knowledge and lists opportunities for a future research.

Chapter 2

Theoretical background and literature review

The aim of this chapter is to provide background information about the iron and steelmaking process via BF-BOF route and highlight important aspects related to bioenergy integration to it. This is achieved by first describing the different units across a typical European integrated steel plant and the specific fuels they consume. The next section then lists the main air pollutants produced across a plant, including measures implemented for their reduction. The third section then outlines conclusions from the state-of-the-art literature on CO_2 abatement using biomass, presented in a form of pros and cons for the fuel switching.

2.1 Iron and steelmaking via BF-BOF route

2.1.1 Process description

Iron ore-based steelmaking via BF-BOF route in Europe occurs at integrated steel plants, where different process units are located close to each other and work simultaneously. The production process is split into multiple stages, which variation across plants depends on the final steel product they produce. As an example, stages taking part within the hot rolled coil (HRC) production are demonstrated in Figure 2.1 and include raw material preparation, ironmaking, steelmaking, slab casting, finishing as well as reheating and rolling.

The key raw materials for steel production via BF-BOF route are limestone, iron ore and coal, which are shipped in bulk amounts to the integrated steel plant [250]. Roughly half of the 300 kg of limestone used for production of one tonne of hot rolled coil is

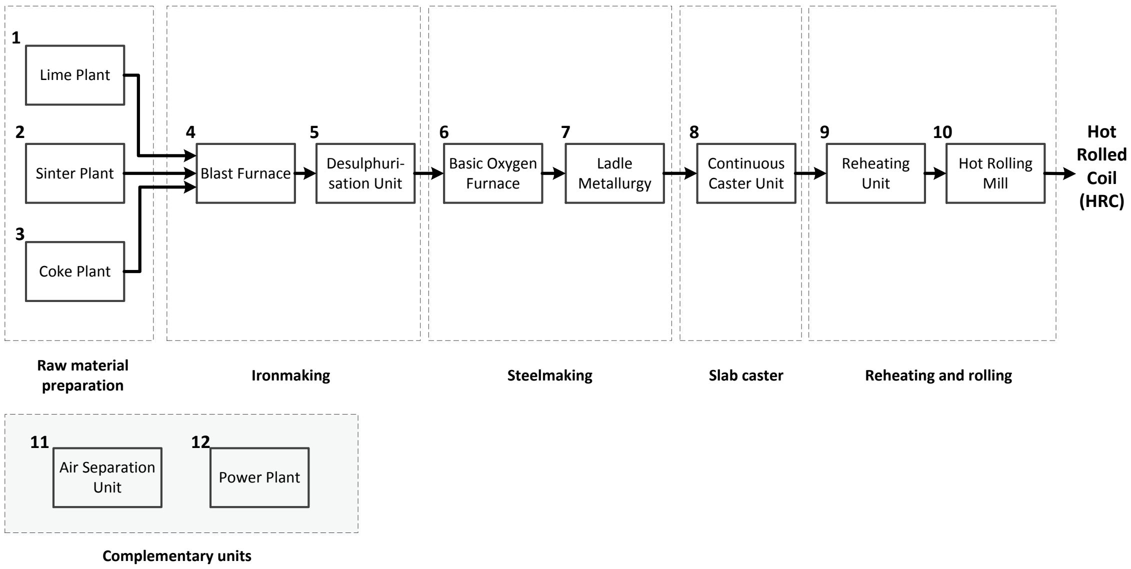


Figure 2.1: Main stages and units involved during the production of hot rolled coil, based on a plant description given in a report published by the IEAGHG [106]. Input of raw materials, such as iron ore and limestone, is not included in the figure boundary.

burned at the lime plant (Unit **1**) to produce lime used during the steelmaking stage to remove impurities [106]. The rest of limestone is bound within sinter in the sinter plant (Unit **2**), which is then fed to the blast furnace, where it removes sulphur and reacts with silica [24]. Iron ore, on the other hand, is first pre-processed in sinter plant to improve the permeability of the burden and hence improve efficiency of the iron ore reduction process in the blast furnace. Generally, for one tonne of hot rolled coil, 1400 kg of iron ore and 650–800 kg of carbon-based fuel is required [106, 250], which exact amount depends on various factors discussed in detail in the next Section 2.1.2. Most of this carbon-based fuel is produced from coal and upgraded in coke plant (Unit **3**), which removes organics and increases the carbon content to over 87 % on dry basis (db) [83]. Enhancing qualities of coke is crucial to be able to provide the required physical support in the blast furnace for the burden [13].

The raw materials are then fed into blast furnace (Unit **4**), where the ironmaking process takes place. The blast furnace is a counter-current reactor, where alternating layers of coke and burden are charged from the top and descent down to the heart [83]. At the same time, hot gas, mainly composited of CO, ascends from the bottom. The hot gas comes from gasification of coke (supplied from the top) and pulverised coal (supplied at the bottom) by a hot blast, blown in through the tuyeres [84].

With an increasing temperature towards the centre, softening and melting of the iron ore begins. Initially, the burden contains around 70 % of iron [83]. To obtain iron content above 95 %, three main reaction stages take place during which the iron oxides are reduced by the carbon based reductants [84]. In detail, first reduction of hematite (Fe_2O_3) to magnetite takes (Fe_3O_4) place. This process generates energy, which increases the temperature of the burden. The magnetite is then reduced to wüstite (FeO), which reaction consumes energy and as the burden is moving down the stack, the burden is softening. Last reduction of the wüstite to iron (Fe) occurs at the bosh of the furnace [236]. Figure 2.2 shows the areas of the blast furnace where those reactions take place. The molten iron and slag are then collected at the bottom.

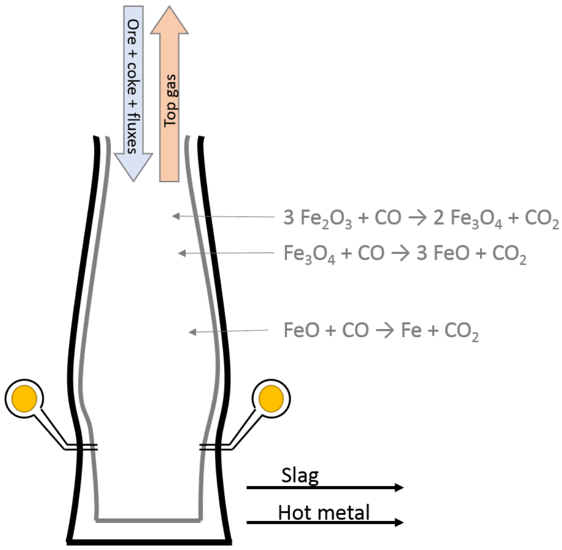


Figure 2.2: Chemical reactions occurring during the reduction of iron ore inside the blast furnace. Figure modified from [83].

The molten iron then goes into desulphurisation unit (Unit **5**), where its sulphur content of around 0.032 % is reduced to less than 0.01 % using calcium carbide (CaC_2) as the desulphurisation agent [106]. The hot metal after ironmaking stage contains high amount of carbon (over 4 %) and other impurities such as silicon, manganese or phosphorus [84]. Those are removed during the next steelmaking stage.

Blast furnace steelmaking is a batch process which starts with the hot metal beings poured into the basic oxygen furnace vessel (Unit **6**), previously charged with steel scrap [106]. Oxygen is blown via lance into the molten metal for typically 15 to 20 minutes, causing reaction:

$$2C + O_2 \longrightarrow 2CO$$

known as the carbon boil [84]. Once the process finishes, the blast furnace vessel is tilted for pouring, and steel is tapped into a ladle car via a taphole, which keeps the slag in the vessel. Within the ladle, further refining of steel takes place to achieve the final steel product of a required quality. This stage is known as ladle metallurgy (Unit **7**) [236]. Molten steel is then sent to continuous caster of two moulds (Unit **8**). Using water and air, the liquid solidifies and then cut into slabs [106].

To obtain a coil from a slab, the slab is first reheated to temperatures around 1200°C in reheating furnaces (Unit **9**) [106]. As the slab leaves the furnace, it goes under a series of pressurised water blasts and through multiple stands in a rolling mill (Unit **10**), which reduces its thickness and extends its width and length to produce a hot steel strip [83]. The final hot rolled coil is obtained from rolling the hot strip onto one of the two coilers, ready to be transported for further treatment.

Apart from units related directly with the iron and steel production process, the integrated steel plants also contain an air separation unit and a power plant [106]. The air separation plant (Unit **11**) takes atmospheric air and separates oxygen and other gases, such as argon and nitrogen [132]. The oxygen is then used in hot stoves and basic oxygen furnace. The power plant (Unit **12**) fires waste gases from blast furnace and basic oxygen furnace to produce electricity. This electricity is then used for various operations across an integrated steel plant [258].

2.1.2 Energy consumption

Ironmaking and steelmaking is highly energy intensive process and fuel cost strongly influences the cost of the final product. As shown in Figure 2.3, fuel and reductant consist of 20 % of the production cost of one tonne of hot rolled coil. This includes coking coal, pulverised coal and natural gas, which are purchased externally. These fuels then generate other types of energy on-site, such as electricity, steam, exhaust gas, coke breeze and coke. A transport network consisting of pipelines, rails and electricity wires are set across the integrated steel plant to maximise use of by-products across the different units. Figure 2.4 demonstrates the complicated energy flow that takes place.

The energy demand for steel production from iron ore is low when compared to the energy required for, e.g., zinc, copper or aluminium production [89]. However, the large demand for steel products places the iron and steel industry as one of the major energy consumers in the world. In total, 28.2 GJ of energy is typically required for the production of one tonne of hot rolled coil [84], but the values can range from 16.7 to 34 GJ ${t_{HRC}}^{-1}$ depending on the furnace efficiency, the deployed system to utilise exhaust gases and waste heat, as well as on the specific technologies adopted on-site [89]. A summary of general

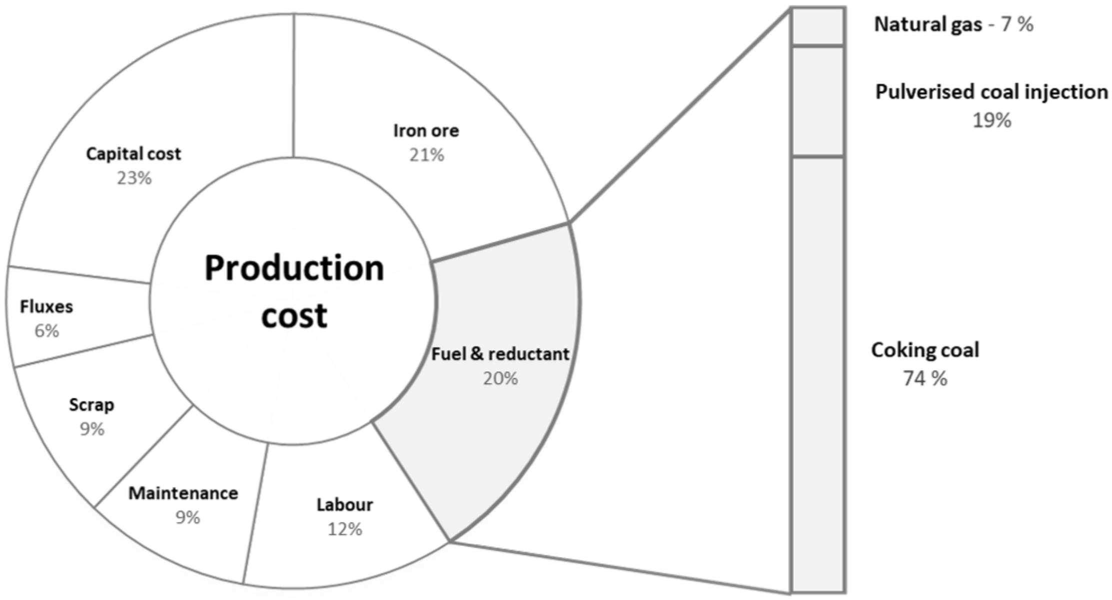


Figure 2.3: Cost split for production of hot rolled coil. Data taken from [106].

heating values and properties of solid and gaseous fuels is presented in Table 2.1 and 2.2, respectively. The coking coal and pulverised coal account for 96 % of the net energy input to the steel plant [106]. The coal quality impacts the blast furnace performance and quality of the hot metal, hence the plant operators are extremely cautious about its characteristics. Other than coal, the plant requires electricity for machinery operation around the site. The plant could either import electricity directly or supply natural gas, which then supports the power generation of the present power plant (Unit **12**). Over half of the energy demand across an integrated steel plant is at the blast furnace (Unit **4**), followed by coke oven (Unit **3**) and reheating unit (Unit **9**). The following section presents further details of each energy type.

Coke

One of the most important material during the ironmaking process is coke. On average, one tonne of hot rolled coil requires 350 kg of coke, originating from 520 kg of coking coal (conversion rates range between 1.25–1.65 tonne of coal for one tonne of coke [99]). Coke has three main roles during the ironmaking process [84]:

- sources carbon monoxide – reducing agent reacting with the iron ore;
- supports the burden – ensures permeability such that gasses can pass through;
- supplies energy – enhances the ongoing chemical reactions;

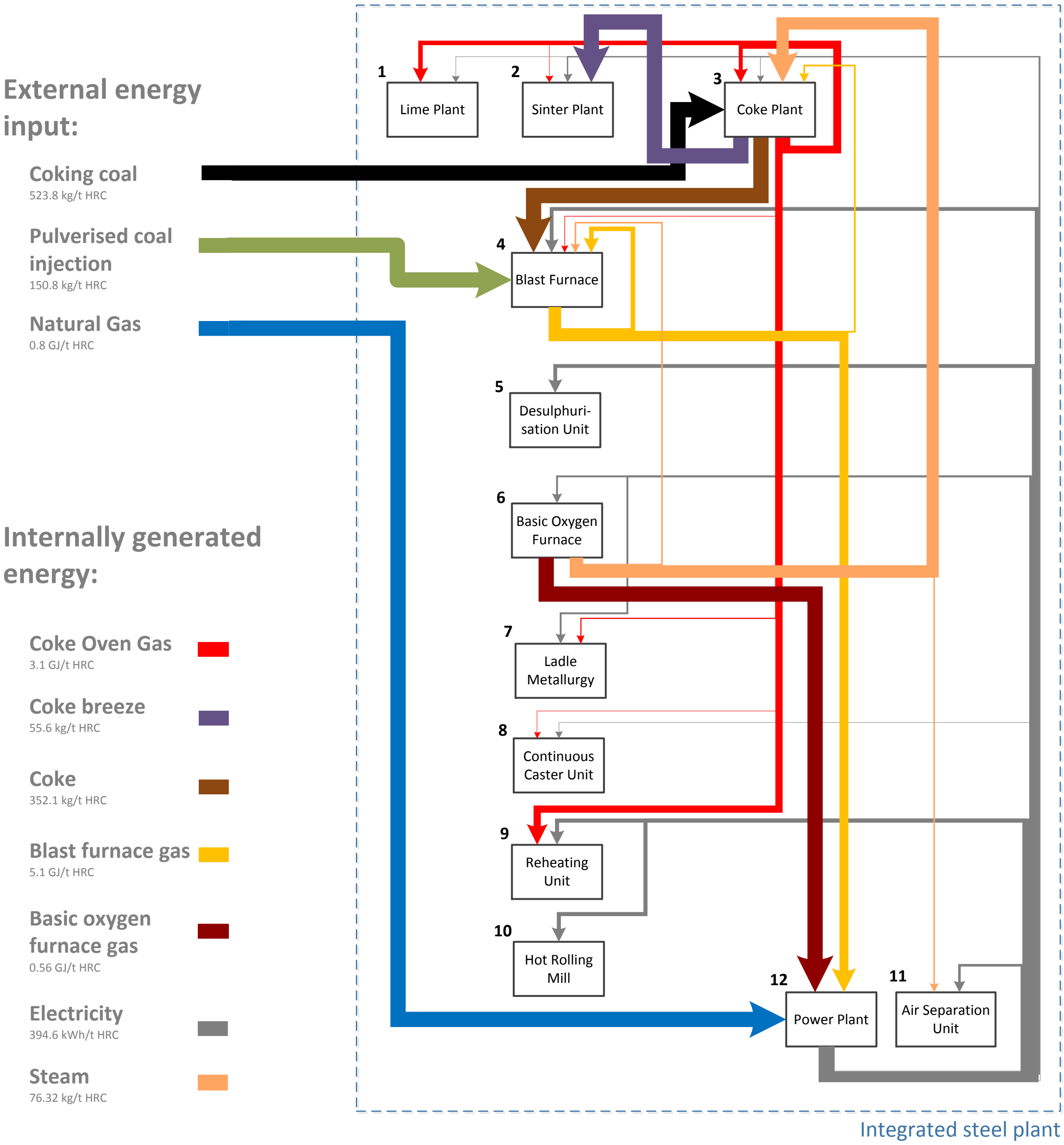


Figure 2.4: Energy flow within an integrated steel plant. Based on data given in [106].

Table 2.1: Properties for solid coal-based fuels used during the iron and steelmaking process. (HHV = High heating value, LHV = Low heating value)

	Coking coal	Coke	Pulverised coal	Coke breeze
Input (kg t_{HRC}^{-1})	523.8 [106], 662.6 [84]	352.1 [106]	150.8 [106], 146.0-214.2 [5]	55.6 [106]
Proximate analysis (ar %)				
Fixed carbon	60.4 [9]	85-88 [89], 83.8[26]	66.9 [26]	84.6 [133]
Volatile matter	24.0 [9]	1-3 [89], <2 [106],1.0 [26]	18.0 [26]	1.4 [133]
Ash	8.2 [9]	>10 [89], 10 [106], 11.2 [26]	7.9 [26]	13.2 [133]
Moisture	7.4 [9]	2-4 [89], 4 [106], 4.94 [6]	6-10 [106]	0.8 [133]
Ultimate analysis (daf %)				
C	85.7 [106], 87.3 [9]	97.8 [106], 83.3 [26], 88[6]	94.5 [106], 74.2 [26], 80.6 [6]	95.7 [133]
H	4.9 [106], 5.7 [9]	0.1 [106], 14.1 [26], 0.35[6]	4.4 [106], 27.4 [26], 4.35[6]	0.4 [133]
N	1.62 [9]	1.2 [106], 9.4 [26], 0.4[6]	4.9 [26], 1.65[6]	1.42 [133]
S	0.9 [9]	0.8-1.3 [89], 0.7 [26, 106], 0.6[6]	0.4 [26], 0.45[6]	0.5 [133]
Heating value (MJ kg^{-1})				
LHV	31.1[106]	27.2-30.1[89], 29.0[106]	33.4 [106]	
HHV	30.2[9]	34.3[26]	32.4[26]	28.5 [133]

- provides carbon – carburises the hot metal;

There are various specific chemical, physico-chemical, physical and mechanical properties that coke has to have (reactivity, heat conductivity, calorific value, cold, hot and micro strength, density and porosity, etc.), where satisfying each is of high importance for the efficiency of the ironmaking process [5]. These properties are ensured via various tests that assess whether the coke used is, for example, resistant enough to fracture during its handling, able to withstand the burden pressure, sufficiently reactive to produce carbon monoxide and after reaction it still has a sufficient permeability. In detail, resistance of coke to fracture is done using the Micum drum test, IRSID test or ASTM tumbler test. Coke reactivity, on the other hand, is assessed using Nippon Steel Corporation (NSC) method, which provides two parameters: coke reactivity index (CRI) and coke strength after reaction (CSR) [84]. Coke of insufficient quality could significantly increase the final coke rate, defined as kilograms of coke consumed per tonne of hot metal produced, causing lower productivity of the blast furnace and higher hot metal cost [196]. For example, Ghosh & Chatterjee [84] state coke rate can increase by roughly 24 kg per tonne of hot metal with every weight percentage increase of ash in the coke. Diez *et al.* [39] also state coke properties could easily influence metal production by 2–3 %. Consequently, quality of coke also impacts the slag volume in blast furnaces. Properties of coking coal and the following coking process is hence highly controlled to obtain the desired coke. European standards require coke of ash content less than 9 % and moisture content less than 5 %. In addition, over 65 % of coke particles should be greater than 10 mm after the CSR test and its CRI should give mass loss less than 23 % [5].

Coke production is also an energy intensive process, where every tonne of produced coke consumes 3.5–5 GJ of energy [99]. At the same time, one tenth of the coke product is not suitable for direct feed into the blast furnace, due to its small size. The production of coke occurs at coke ovens, where coking coal is heated up to 1000 to 1200°C, in the absence of oxygen, for several hours to reduce its volatile and moisture content. Due to the non-occurrence of combustion, the generated coke oven gas is particularly rich in hydrogen [99] and of a relatively high heating value, as Table 2.2 shows. From Figure 2.4 it can be observed that coke oven gas is widely used across the integrated steel plant, particularly in reheating unit (Unit **9**), lime plant (Unit **1**), sinter plant (Unit **2**) as well as in the coke plant itself (Unit **3**).

Coking coal

As mentioned earlier, properties of coke are highly dependant on the coal it is produced from. Types of coal are classified based on the degree of coalification reactions they have undertaken, broadly defined as coal rank. Main coal ranks are lignite, bituminous coal and anthracite, which are then further split into sub-bituminous, semianthracite, etc. As Figure 2.5 shows, the coal rank increases with decreasing moisture and volatile matter, and increasing fixed carbon and energy content [84]. Coking coals belong under bituminous coals, which reserves are the biggest in the world [246]. However, only a small share of bituminous coals is actually suitable for coke production. The selection of coal for coke-making is made based on chemical (proximate and ultimate analysis), rheological (passing through stages of softening, swelling, becoming semi-plastic and completely plastic before solidifying into coke), dilatometric (swelling of coal due to pressure from volatile matter), agglomerating properties (ability to form a mass) and petrographic analysis (defining coal rank and mineral composition) [84]. The increasing requirements on the coke quality and, consequently, the limited availability and high cost of prime coking coals introduced coal blending. The blending is done using various prediction models, which are able to estimate the final coke strength as well as CRI and CSR indices based on the properties and mixture of the different coals [39].

In general, coking coal has to have moisture content below 10 %, volatile matter between 20 and 35 % (db), and ash less than 10 % (db). Strict criteria are also given for phosphorus and sulphur content of the coal, limited to maximum 0.1 and 0.6 % (db), respectively [195]. Typical values of coking coals provided the existing literature can be found in Table 2.1.

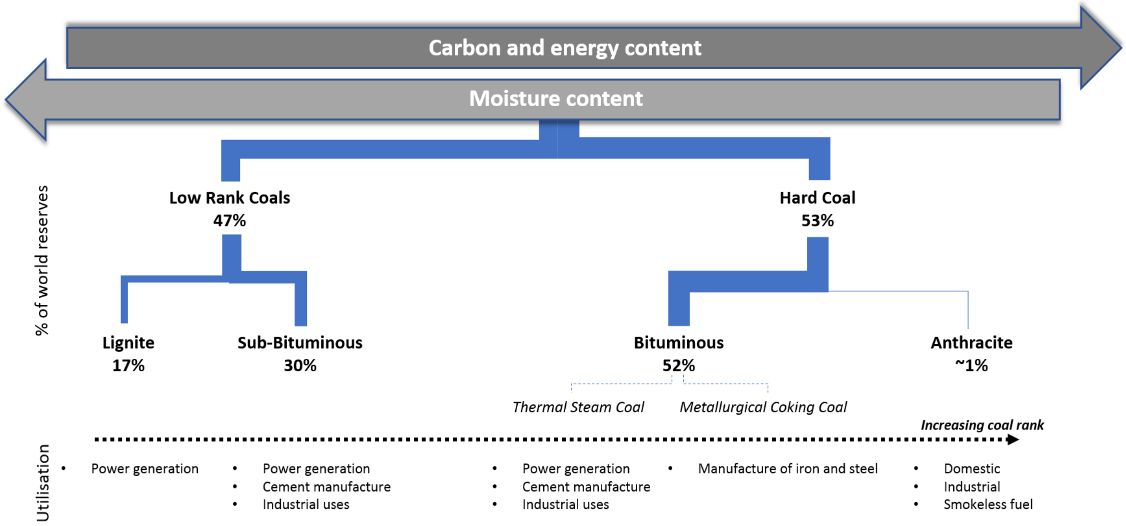


Figure 2.5: Overview of main coal ranks and comparison of their properties, world reserves and their common applications. Figure adopted from [246].

Pulverised coal

Use of pulverised coal injection (PCI) reduces the consumption of expensive metallurgical coke and an overall energy demand by an integrated steel plant. Injection of pulverised coal also positively influences the productivity of blast furnace, assists in maintaining its stability, reduces the silicon content in the hot metal and improves the overall quality of it. Pulverised coal injection also presents plant operators a better opportunity to adjust the thermal conditions in the furnace [197]. Coke can be replaced by pulverised coal in a ratio 0.9 to 1.0 [13]. Pulverised coal is introduced into the lower part of the blast furnace, where through lances it is blown into the tuyeres [106]. It works as an additional carbon source, where it first reacts with the oxygen of the blast and generates CO_2. The CO_2 then reacts with burning hot coke resulting in production of the required CO [5]. Pulverised coal is, same as coking coal, a blend of different coals, ranging from high volatile lignite to low volatile anthracite [197]. Its mixture allows to control the coal quality and overall cost of fuels. However, the different properties of the coals make the combustion performance of the blend complex [201]. The mixture and the amount of pulverised coal that could be used is apart from properties of the coals also influenced by the coke quality. Global average of pulverised coal usage is around 125 kg $t_{HM}{}^{-1}$, however, some plants can operate with injection rate up to 200 kg $t_{HM}{}^{-1}$ [99].

The required properties and injection rate of pulverised coal is often site specific, but the demand on coal quality increases with increasing injection rates. One of the key criteria for pulverised coal is low ash, phosphorus and sulphur content. High ash content would result in increased slag volumes in the furnace and permeability problems in the lower part of the blast furnace. The desired ash content should hence be below 9 % (ar) and any further increase negatively impacts the coke replacement ratio. Similarly, phosphorus levels should be less than 0.05 % and sulphur less than 0.6 % to ensure quality of the hot metal. Moisture content is also monitored for the pulverised coal to below 10 %, as higher moisture content coal can cause blockage during transport to the blast furnace [197]. For tuyere injection, both high and low volatile content coals are used, where the high volatile coal could reach a higher burnout due to a stronger devolatilization. At the same time, high volatile coals create a greater blast momentum and increase the depth of the raceway. Apart from the listed chemical characteristics, the coals must have sufficient grindability, handleability, combustibility and reactivity. For example, the pulverised coal must have high combustion efficiency, as otherwise unburned coal can cause a decrease in permeability in the furnace. A large amount of unburned char in slag or top gas then reduces the coke replacement ratio [197].

Apart from coal, an experience exists with injecting oil, natural gas, hot reducing gases, waste plastic, old tyres or biomass. Injection of oil was a popular practice to enhance the productivity and control the furnace before the oil crisis in the 1970s [145], but an oil injection is still practiced, for example in the Finnish steel mill Ruukki [134]. Operation of blast furnaces with natural gas could be found in USA, Russia and Ukraine of injection rate between 155-170 m^3 ${t_{HM}}^{-1}$ [7]. Industrial deployment of plastic injection has been done particularly in Germany, Japan and Korea [259]. The behaviour of plastic is reported to be similar to oil injection [259]. However, the plastic injection causes problems due to its high chlorine (Cl) values, which can form hydrogen chloride (HCl) and cause corrosion of the walls, as well as impact the flame. Therefore, Janz & Weiss [115] suggest that injection rate of plastic should not be more than 35 kg ${t_{HM}}^{-1}$.

Coke breeze

Coke breeze, i.e., fines of coke produced at coke oven, is used as fuel in the sintering process. General input is around 55.6 kg ${t_{HRC}}^{-1}$ (or 50.0 kg ${t_{sinter}}^{-1}$) [106] and its size is less than 5 mm [183]. Umadevi *et al.* [219] show that the quality of the sinter and its microstructure is influenced by the coke breeze particle size, and therefore the majority of coke breeze should be of size less than 3 mm to achieve the best sinter properties. Often, coke breeze production during coking is insufficient to meet the demand from the sinter plant, hence it is common that plants purchase additional fuels from external suppliers [183].

Table 2.2: Composition and calorific value of gas-based fuels used across an integrated steel plant.

	Coke oven gas	Blast furnace gas	Basic oxygen furnace gas	Natural gas
Input (GJ t_{HRC}^{-1})	3.1 [106]	5.1 [106]	0.56 [106]	0.8[106]
Composition (vol%)				
H_2	57.0 [84], 59.0 [69]	3.7 [84], 3.59 [106], 3.0 [69]	2.64 [106], – [69]	– [84]
CO	5.9 [84], 5.0 [69]	26.3 [84], 22.10 [106], 21.0 [69]	56.92 [106], 70.0 [69]	– [84]
CH_4	29.7 [84], 28.0 [69]	– [69, 84]	– [69]	94.5 [84], 83.90 [106]
C_2H_6	1.1 [84], 4.0 [69]	– [69, 84]	– [69]	0.5 [84], 9.20 [106]
N_2	0.7 [84], 3.0 [69]	57.1 [84], 48.24 [106], 56.0 [69]	13.83 [106], 14.0 [69]	4.0 [84], 0.40 [106]
CO_2	1.5 [84], 5.0 [69]	12.9 [84], 21.86 [106], 20.0 [69]	14.44 [106], 16.0 [69]	0.2 [84], 1.80 [106]
O_2	– [69, 84], 0.19[106]	– [69, 84]	– [69]	0.3 [84]
Calorific value (MJ m^{-3})				
	21.5 [84], 19.8 [69]	3.9 [84], 3.18 [106], 3.0 [69]	7.47 [106], 8.8 [69]	35.7 [84], 40.64 [106]

Coke oven gas

Coke oven gas is a by-product produced from cokemaking at the coke oven batteries. One tonne of coal yields approximately 285-345 m^3 of coke oven gas [84]. As Table 2.2 shows, it is of a medium calorific value and consists mainly of hydrogen and methane. The coke oven gas is processed to remove the tar, naphthalene, benzene/toluene/xylene (BTX), H_2S, ammonia and particulates, which were released from coal during the cokemaking process [106]. Clean coke oven gas is then used as a fuel across most of the units within the integrated steel plant, as shown in Figure 2.4, either on its own, or to enrich the calorific value of other process gasses [183].

Blast furnace gas

Out of all gases generated on-site of the integrated steel plant, blast furnace gas is of the lowest calorific value (Table 2.2). Its properties depend on the operating conditions, such as amount of indirect reduction in the furnace shaft, extent of oxygen enrichment of the blast or the fuel rate in the furnace [84]. Due to containing a high amount of solid particles, wet-type or dry-type gas cleaning is necessary. The low calorific content makes its use mainly at units requiring low-temperature heat, such as hot stoves and coke oven plant. Leftover gas is sometimes also used for power and steam generation (Figure 2.4). Every tonne of hot metal produces roughly 1500 to 1700 Nm^3 of such blast furnace gas [84].

Basic oxygen furnace gas

Basic oxygen furnace gas is medium calorific value gas produced at the basic oxygen furnace. Majority of it is CO, but a high amount of solid particles requires its cleaning or scrubbing [183]. This gas is mainly used within the power plant (Figure 2.4).

2.2 Air pollutants and measures for their reduction

Production of iron and steel via BF-BOF route is one of the most polluting processes across the whole industry sector. Measures to reduce pollution of air, water, soil as well as noise are implemented to decrease its impact on the environment. Out of all of the pollutants mentioned, air pollution is possibly the most significant as large amounts of dust, volatile organic compounds (VOCs), CO_2, SO_2 and NO_x are produced across different units. Exposure to pollutants can lead to serious impacts on human health, which can range from nausea, difficulty in breathing and skin irritation to cancer. Moreover, air pollution could be responsible for birth defects or reduced activity of immune systems [118]. Air pollutants are also known for disintegrating the ozone layer [71] and global warming. This section discusses the most common air pollutants produced during the process in further details and lists measures deployed for their offsetting.

2.2.1 Dust

Dust is generated across all units within an integrated steel plant from the occurring chemical processes or handling of raw materials, and could easily amount up to 56 kg of dust for every tonne of crude steel produced [84]. Its high concentrations occur particularly around the furnace, casting and fabrication areas [91]. Dust exposure can create respiratory problems, lung diseases or skin irritations, which may become obvious only after long-term exposures. Apart from the health risks, dust formation of combustible materials can also cause fire and explosion [243].

Dust levels from flue gases are reduced using extraction systems with bag filters, electrostatic precipitators, cyclones or wet scrubbers and sometimes recycled back to the system. Techniques to reduce the dust released from handling, transport and storage of raw materials across integrated steel plants include deployment of dust-suppressing water sprays or creation of embankments and planting vegetation, which prevent its blowing around [183].

2.2.2 VOCs

Coke oven batteries present the biggest danger of VOCs emissions. Good coke oven operation and maintenance deployed together with dry quenching practice minimises the VOCs significantly [89]. Reduction of the VOCs is also achieved by using materials with lower organic compounds or their recycling [84]. Exposure to the VOCs is know to cause liver and kidney problems as well as irritation of the respiratory tract [89]. Production of one tonne of crude steel generates around 0.3 kg of the VOCs [84].

2.2.3 SO_x

Another controlled air pollutant is SO_x, to which long-period exposure could cause severe bronchial spasm. Further oxidation of SO_2 can also known to cause acid rain. As most of the sulphur occurring during the process comes from coal, a noticeable decrease in SO_x emissions could be achieved purely by switching from high- to low-sulphur coals [89]. Generally, 2.2 kg of SO_2 is generated per tonne of crude steel [84]. Remus *et al.* [183] in the BAT reference document for iron and steel production stress the existence of sulphur compounds particularly in the coke breeze. Therefore, reduction in the coke breeze consumption or switching to materials with lower sulphur content (of which biomass is an example) should be considered. Desulphurisation of the flue gas, to remove sulphur compounds occurring later at the stream, could be done using wet, dry or semi-dry processes [84].

2.2.4 NO_x

Respiratory and heart diseases are also caused by NO_x emissions. Apart from using coal with lower nitrogen content, e.g., anthracite, process such as selective catalytic reduction could be deployed [183]. During this process, NO_x is catalytically reduced to urea or ammonia and water. Despite the deployment of such measures, 2.3 kg of NO_x is generated with every tonne of crude steel produced [84].

2.2.5 CO_2

CO_2 emissions are produced from natural as well as man-made sources and the corresponding heath problems depend on the level of CO_2 concentration an individual is exposed to. Therefore, sufficient control measures are installed around the plant to protect the plant operators. Apart from the health hazard, concerns related to CO_2 emission production are due to it being a heat-trapping greenhouse gas, which increasing concentration in the atmosphere is contributing to global warming.

Norgate *et al.* [165] estimate the CO_2 emission intensity of crude steel production within an integrated steel plant to 2.17 $t_{CO_2}\ {t_{CS}}^{-1}$, considering the system boundary as cradle-to-gate. This is an estimate close to the value obtained in a report by IEAGHG [106] of 2.094 $t_{CO_2}\ {t_{HRC}}^{-1}$, which only accounts for on-site emissions. Production of CO_2 is inevitable as they are linked to the energy consumption, in a form of coal, within the plant. Assigning the emission intensity to each unit is complicated as by-products of iron and steelmaking processes are further used during the process, as shown in Figure 2.4. The most CO_2 emissions is released into the atmosphere from a power plant unit, as shown in Figure 2.6, followed by blast furnace, sinter plant and coke plant. However, it is important to note that the high amount of power plant emissions result from producing electricity from by-products generated across other units.

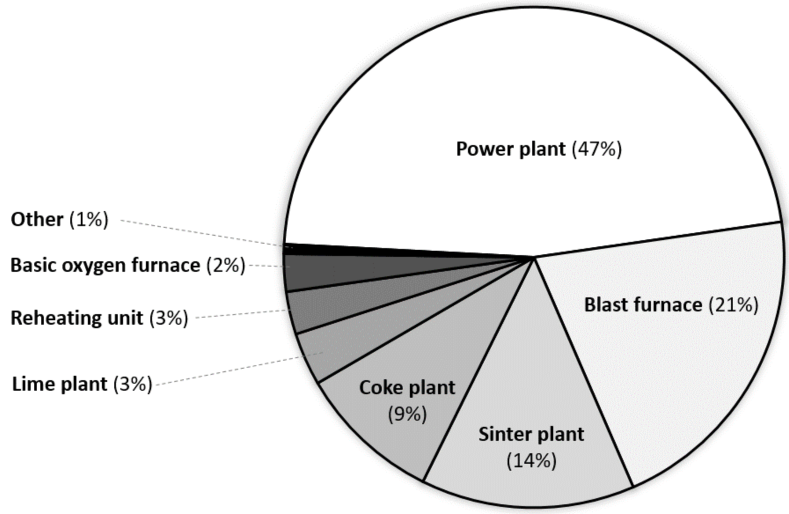


Figure 2.6: Share of CO_2 emissions emitted into the atmosphere at each unit during the production of hot rolled coil. Data taken from [106].

Section 1.2 and 1.3 previously discussed the technologies and practices that could reduce the CO_2 emissions. The next section focuses specifically on bioenergy and the related aspects required to consider when it is deployed as a CO_2 reduction measure across an integrated steel plant.

2.3 Review of bioenergy opportunities within the BF-BOF route

2.3.1 Possibilities for fossil fuel replacements

A possibility for direct fossil fuel replacement, without a requirement for major modification of the technologies set in place, is the main advantage of bioenergy over other renewables. Depending on the type of feedstock and upgrading process, biomass-derived products could be of a composition and characteristics very close to the fossil fuels used during the iron and steelmaking process. The existing literature discussed particularly three units across an integrated steel plant for which bio-based products could be considered. Those include coke oven, sinter plant and blast furnace. The identified opportunities for each one of them are further discussed in this section, accompanied by Table 2.3 summarising the considered amount of fuel substitution by each individual study.

Potential for biomass use in coke ovens

The stringent requirements on physical, chemical and thermal qualities of the final coke product, as described in Section 2.1.2, make substitution of coking coal by bio-based products very limited. Particularly the physical requirement for high strength coke in the European blast furnaces allows only small substitution of coking coal by bio-based products for each tonne of hot rolled coil [155]. But even a small amount could lead to significant CO_2 emissions reductions in total. Especially when considering a wide-scale deployment across different plants, which in the EU produce on average 4 million tonnes of hot rolled coil a year [33]. On top, the final coke is the most expensive energy input during the process [106] and a use of alternative fuels for its production could decrease its final cost.

Utilisation of a variety of bio-based fuels within coke ovens is very limited, even the ones which have been thermally pre-treated. Matsumura *et al.* [147], focusing on raw wood biomass, shows that compacted biomass at room temperature could substitute coking coal during cokemaking up to 1.5 %. Similar findings exist for raw sawdust with recommend substitution below 2 % as well [153]. Raw biomass is known for its low calorific value, low density and high moisture content, which significantly degrade its quality as a fuel for coking coal substitution. Just its compressing at a temperature of 200°C increases the bio-based product's density and consequentially increase its technically feasible substitution to 3 % [147]. The most energy dense form of bio-based fuel is charcoal, obtained from slow pyrolysis, which makes it a widely considered fuel for the coking coal substitution by the existing literature. Findings presented by Hanrot *et al.* [93] from SHOCOM (Short-term CO_2 mitigation for steelmaking [49]) project state that 3 % substitution by charcoal should not impact the final coke properties. The same limit is defined by Ng *et al.* [160], which studied blends up to 5 %. Surprisingly, non-experimental studies are considering charcoal blends up to 10 % [146, 165]. However, those estimates are only based on mass and heat balance calculations, and do not consider the complete list of properties that the final coke has to have to full-fill all of the functions in the blast furnace. The technical studies considering 10 % blends point out that the resulting coke would certainly be of a lower quality, but the specific quality degradation is dependant on bulk density, particle size

Table 2.3: Possibilities for coal-based fossil fuel substitution by different bio-based fuels.

Initial fossil fuel used • Bio-fuel type substituted	**Considered substitution**	**Estimated CO_2 offset**	**Ref.**
Coking coal			
• Compacted woody biomass:	· 2-3 %	–	[147]
• Sawdust:	· 2 %	–	[153]
• Charcoal:	· up to 5 %	0.06 $t_{CO_2} t_{HM}^{-1}$	[160]
	· up to 10 %	–	[136]
	· 2-10 %	0.02–0.11 $t_{CO_2} t_{CS}^{-1}$	[146]
	· 2.5-10 %	–	[208]
	· 2-10 %	0.02–0.10 $t_{CO_2} t_{CS}^{-1}$ (BPCs: 0.02–0.14 $t_{CO_2} t_{CS}^{-1}$)	[165]
• Kraft-lignin:	· 2.5-10%	–	[208]
Coke breeze			
• Charcoal:	· 50-100 %	0.11-0.30 $t_{CO_2} t_{CS}^{-1}$ (BPCs: 0.15-0.39 $t_{CO_2} t_{CS}^{-1}$)	[165]
	· 50-100 %	0.12-0.32 t_{CO_2} t_{CS}^{-1}	[146]
	· optimal 25 %	–	[156]
	· up to 40 %	43 kg_{CO_2} t_{sinter}^{-1}	[117]
	· below 50 %	–	[133]
	· 40 %	18.65 % t_{sinter}^{-1}	[82]
• Wood pellets & olive pits:	· 15 %	0.02 $t_{CO_2} t_{HRC}^{-1}$	[178]
• Sawdust & charred-straw:	· 15-20 %	5.39-7.19 % t_{sinter}^{-1}	[82]
Coke			
• Charcoal:	· 22-45 kg t_{HM}^{-1}	0.08-0.16 $t_{CO_2} t_{CS}^{-1}$	[146]
	· 20-50 kg t_{HM}^{-1}	6.0 kg_{CO_2} $kg_{charcoal}^{-1}$	[94]
Pulverised Coal			
• Charcoal:	· up to 100 %	0.41-0.55 $t_{CO_2} t_{CS}^{-1}$	[146]
	· 100 %	–	[6]
	· up to 100 %	0.509 $t_{CO_2} t_{HM}^{-1}$	[237]
• Torrefied fuel:	· up to 22.8 %	0.116 $t_{CO_2} t_{HM}^{-1}$	[237]
• Pellets:	· up to 20.0 %	0.102 $t_{CO_2} t_{HM}^{-1}$	[237]
• Hydrochar:	· up to 25.2 %	–	[238]
Heavy oil			
• Bio-oil	· 140 kg t_{HM}^{-1}	0.06$t_{CO_2} t_{HM}^{-1}$	[159]

BPCs Considering by-product credits, assuming off-gases from charcoal production will be used for electricity and heat generation.

and specific charcoal composition, not just the blend percentage itself [136, 208]. It can be also assumed that the exact requirements on the final coke quality would be different for each blast furnace considering its deployment, as every blast furnace is unique in its operation, technical specifications, etc. The 100 % charcoal blast furnaces in Brazil are a good example of this. Their smaller heart diameter (1.5 to 6 m) than traditional coke blast furnaces (around 14 m) require less stringent fuel characteristics [27]. Based on this it can be assumed that coking coal substitution by charcoal of 10 % could be technically feasible for certain plants, but not for all. Comparison of the specific technical restrictions for charcoal substitution across different blast furnaces that would support such statement unfortunately does not exist, as far as the author is aware.

Certain properties of bio-based fuels could even improve the blast furnace operational performance. For instance, Hanrot *et al.* [93] point out that the coke produced from coking coal blends with charcoal has higher reactivity. As a result, charcoal addition lowers the temperature of Boudouard reaction (where the carbon in coke reacts with CO_2 and forms CO) by 100 to 200°C, which leads to a lower carbon consumption [155]. Increase of reactivity of the final coke whilst increasing share of raw biomass is also observed by Jeong *et al.* [116]. Such trait could potentially further enhance the CO_2 emission reduction potential by biomass, beyond just substituting fossil-carbon by bio-based carbon stated by the exiting literature to around 0.10 t_{CO_2} ${t_{CS}}^{-1}$ (as shown in Table 2.3). On the other hand, the physical characteristics of bio-based fuels could deteriorate the coke strength and hence the efficient blast furnace operation. Previous studies focused specifically on its impact on the coke strength, but their findings differ, possibly due to the differences in the methodologies they have applied. For example, Ng *et al.* [161] use three charcoal particle size groups: <0.07 mm, 2.4-3.4 mm and 6.4-9.5 mm and show an overall reduction in CSR. The findings also show that the CSR reduction is more significant for fine rather than coarse charcoal. A study by Suopajärvi *et al.* [208] focuses rather on the cold compressive strength and particle sizes below 2 mm. The findings show coke from a charcoal blend is of comparable cold compressive strength to the reference coke, where the tests specifically with charcoal of particle size between 0.124-250 mm present even an increase in the cold compressive strength. Interestingly, Suopajärvi *et al.* [208] mention the results by Ng *et al.* [161] and state that both studies observe a similar impact of the particle size. However, such statement should be questioned. First as the two studies observe a different trend in terms of the impact of the particle size and second, the cold compressive strength used by Suopajärvi *et al.* [208] and CSR used by Ng *et al.* [161] are two different measures. The present author recommends performing further research to accurately understand the impact of particle size on cold compressive strength and CSR to be able to support such statement. Apart from the properties and specifications of the charcoal used, the properties of the coals that are blended with charcoal are also important. Mousa *et al.* [155] state that coals with higher reactive-to-inert ratio and low amount of inertinite, structure which limits coals' burning behaviour and ignition during the combustion, could achieve higher level of charcoal blends. Therefore, when defining the maximum level of coking coal substitution, specifications of the coal should be taken into the consideration as well.

Potential for biomass use in sinter plant

Requirements on the fuels used at a sinter plant are much less stringent than on the ones at the coke oven, as the fuels used at a sinter plant have mainly thermal function. However, biomass still should be pre-processed to reduce moisture and increase its calorific value and carbon content. Non-experimental studies have considered coke breeze replacement with charcoal up to 100 % [146, 165]. However, studies focusing in detail on the sintering performance and sinter quality suggest a maximum replacement at much lower levels, i.e., below 50 % substitution rate. For example, Gan *et al.* [82] define the maximum substitution of 40 %, Mousa *et al.* [156] identify the optimum substitution even lower at 25 % (both for charcoal). The difference between the maximum substitution of 25 % and 40 % could be just due to the blend ratios studied by each study, as Mousa *et al.* [156] consider charcoal blends of 0, 25, 50 and 100 % whereas Gan *et al.* [82] consider charcoal blends of 0, 20, 40, 60, 80 and 100 %. In other words, if both studies have considered the same blend percentages, they might recommend the same percentage blend in the end. Apart from charcoal, other bio-products have been also studied, e.g., charred-straw, molded-sawdust, wood pellets or olive pits, but each shows opportunities for small substitution ratio below 15 % [82, 178].

Utilisation of bio-based products raises concerns mainly about preserving the required sinter quality. In detail, Lu *et al.* [133] show the negative impact of coke breeze substitution by charcoal on the balance of return fines, strength of the sinter (measured by tumble strength and reduction disintegration) and increase in fuel addition. Similarly, Gan *et al.* [82] and Mousa *et al.* [156] demonstrate reduction in sinter quality as product yield and tumbler index decrease with increasing blends. The final sinter is also observed to be of a lower density and being less compacted for mixtures containing charcoal than for the pure fossil fuel ones. Due to charcoal having higher moisture saturation properties than coke breeze, it is more likely to absorb moisture from the blend. To maintain granulation efficiency, linked to the pre-ignition airflow across the sinter mix, the blend has to have a higher moisture content as a result [133].

On the other hand, bio-products could improve the overall performance of the sinter plant. The study by Gan *et al.* [82] shows an increase in vertical sintering speed, whilst permeability stays consistent even during 100 % charcoal utilisation. However, a complete opposite is observed by Mousa *et al.* [156] showing a significant decrease in bed permeability with increasing charcoal blends, which they reason by charcoal having lower strength than coke breeze. As bed permeability is related to vertical sintering speed and sintering time [31], the observations of the two studies on the sinter productivity actually contradict each other. The reason for the different observations might be the difference in the sintering process and the equipment use. Therefore, real life considerations for charcoal should try to imitate sintering process described by Gan *et al.* [82] to achieve the best results.

Coke breeze could reduce a wide range of pollutants other than just CO_2 emissions. Both Lu *et al.* [133] and Gan *et al.* [82] observe that with an increasing coke breeze substitution by charcoal, concentrations of SO_x and NO_x in the waste gas reduce. For example, 40 % replacement of coke breeze with charcoal reduces SO_x by 38.15 % and NO_x by 26.76 % [82]. Reducing SO_x and NO_x emissions as a result of fuel switching could offset costs that currently occur from their reduction by different methods, as discussed previously in Section 2.2.3 and 2.2.4, creating a potential economic benefit. This economic benefit should be explored further in a techno-economic analysis of biomass utilisation across an integrated steel plant to investigate whether the SO_x and NO_x reduction could become a bigger driver for biomass deployment than the CO_2 reduction initially intended for.

Potential for biomass use in a blast furnace

Across a blast furnace, bio-based products could partially substitute coke charged from the top, or pulverised coal injected from the bottom. Directly charging bio-based products from the top, however, is a much less discussed possibility across the literature. This is possibly because modern blast furnaces have specific requirements for the coke, and biomass would be rather charged from the top in a form of bio-agglomerate, i.e. in a form of bio-coke or bio-sinter, production of which was discussed earlier. Despite the use of bio-agglomerates, work by Mathieson *et al.* [146] considers the possibility of directly replacing 50–100 % of 45 kg of nut coke used for the production of one tonne of hot metal. Similar finding is given by work by Hanrot *et al.* [94], which suggests 20–50 kg $t_{HM}{}^{-1}$ of charcoal mixed with coke. The findings define an expected reduction in the thermal reserve zone temperature by around 100°C and decreases the coke rate by 20 kg ${t_{HM}}^{-1}$, which leads to saving energy. However, any greater substitution would be very hard across large blast furnaces, which exist in the EU. Mousa *et al.* [155] discuss the absence of sufficient thermal plasticity of biomass that gives a low crushing strength to the iron ore-biomass composite, which utilisation in high amounts would lead to the collapse of the burden within the blast furnaces.

A flexible option for biomass utilisation is by tuyeres injection at the bottom of the furnace (sometimes referred to as bio-PCI). Such choice presents the greatest possibilities for biomass integration across the whole integrated steel plant due to a relatively low demand on the fuel properties. At the same time, the injection of charcoal presents comparable or even better combustion behaviour than ordinary PCI [6]. Therefore, its utilisation could even improve the operation of the furnace, but only if the charcoal has specific properties achieved from strict control of the carbonisation conditions used during its production [6, 94]. Generally, studies have considered a 100 % replacement of pulverised coal by charcoal [6, 146, 237]. However, a study by Hanrot *et al.* [94] mentions that only partial substitution is realistic for the case of European blast furnaces when considering all the energy, environmental and social issues. This is indeed an important statement which highlights that the technical aspect is not the only barrier for large scale charcoal deployment across the iron and steelmaking process.

Apart from charcoal, other bio-based fuels have been also considered for the bottom injection into the blast furnace. Using a modelling approach, Wang *et al.* [237] states that up to 22.8 % and 20 % by weight could be substituted by torrefied material and wood pellets, respectively, considering initial pulverised coal use of 155.5 kg ${t_{HM}}^{-1}$. A possible reason for such a low substitution ratio is the high volatile matter in those bio-based fuels, which reduce the raceway adiabatic flame temperature and so addition of oxygen in the blast furnace would be required to sustain such temperature. Wang *et al.* [238] also considers utilisation of waste in a form of hydrochar, allowing substitution up to 25.2 % by weight. Overall, the lower calorific value and the porous nature of bio-based fuels in comparison to coal present particular difficulties for biomass injection in sufficient rates [155]. Therefore, bio-based fuels other than charcoal should be considered in further studies, as they can present a cost-efficient way for bioenergy utilisation, even though a significant emission reduction should not be expected. The net environmental benefit could improve if the focus is also on the emissions occurring across the whole life cycle, particularly when dealing with waste-based feedstock. In detail, each tonne of bio-based waste which is disposed to landfill generates around 2.1 t_{CO_2}eq [130]. Diverting this waste from landfill and further utilising it in a blast furnace can offset a significant amount of emissions, before even accounting for the emissions offset from the fossil fuels substitution. Such potential environmental benefit should be remembered when dealing with waste-based feedstock. Apart from solid biomass, Suopajärvi *et al.* [206] also consider bio-reducers in a form of bio-oil (from fast pyrolysis) and bio-SNG (from gasification and methanation). Such reducers, however, are not suitable for most EU integrated plants as majority of the blast furnaces are built to inject solid material and hence additional modification would be required.

2.3.2 Advantages of using biomass within the process

Net CO_2 emission savings

Based on the assumption of carbon neutrality, biomass deployment across an integrated steel plant presents opportunities for significant CO_2 emissions reduction. Mathieson *et al.* [146] identify emission savings from charcoal partially replacing fossil fuels as 0.02–0.11 $t_{CO_2}\ {t_{CS}}^{-1}$ for coking coal, 0.12 to 0.32 $t_{CO_2}\ {t_{CS}}^{-1}$ for coke breeze, 0.41 to 0.55 $t_{CO_2}\ {t_{CS}}^{-1}$ for pulverised coal and 0.08 to 0.16 $t_{CO_2}\ {t_{CS}}^{-1}$ for nut coke. This is equivalent to a total emission saving estimate range of 0.63–1.14 $t_{CO_2}\ {t_{CS}}^{-1}$ (29–52 %). Other literature sources provide different estimates due to using different substitution ratios as well as assumptions for the emission calculation. For example, Ng *et al.* [160] estimate emission savings for coking coal only a maximum of 0.06 $t_{CO_2}\ {t_{HM}}^{-1}$, due to maximum 5 % substitution potential (work by Mathieson *et al.* [146] considers up to 10 % substitution). The case is similar for other literature sources too, as summarised previously in Table 2.3. Apart from the four main possibilities for biomass substitution, it is important to note that work by Mathieson *et al.* [146] and Norgate *et al.* [165] also consider 100 % replacement of char at the steelmaking recarburiser, where roughly 0.25 kg of char is used for every tonne of crude steel. This is a small amount of carbon input resulting in negligible CO_2 emission savings (0.001 $t_{CO_2}\ {t_{CS}}^{-1}$), and its inclusion would not impact the CO_2 emission reduction potential of bioenergy across an integrated plant.

Similarly, production of the bio-products could have a significant carbon footprint and it is hence important to control the production process such that an overall CO_2 reduction is achieved. Brack [20] in a report produced by Chatham House states that carbon-neutrality of biomass should not be assumed as biomass might emit more CO_2 per unit of energy than most fossil fuels, if the emissions resulting from the land use change emissions are taken into consideration. Considering emissions produced from plantation establishment and management, harvesting and transport, Norgate *et al.* [165] provide a general estimate of the emission intensity of charcoal production of 0.105 t_{CO_2} ${t_{charcoal}}^{-1}$. Work by Suopajärvi *et al.* [207] estimates a higher value of 0.214–0.267 t_{CO_2} ${t_{charcoal}}^{-1}$, when focusing specifically on charcoal production for blast furnace application in Finland. It is important to note that Norgate *et al.* [165] do not consider in their estimate emissions from fertilisation. Considering the emissions associated to the use of fertilisation estimated to 0.214–0.267 t_{CO_2} ${t_{charcoal}}^{-1}$ by Suopajärvi *et al.* [207], the values of Norgate *et al.* [165] would increase to around 0.345 t_{CO_2} ${t_{charcoal}}^{-1}$. Accounting also for the indirect emissions from the soil carbon stock change gives a total environmental impact of 1.3–3.5 t_{CO_2} ${t_{charcoal}}^{-1}$. This could indeed completely diminish the amount of CO_2 emissions that charcoal could offset in the first place, which is around 2.89 t_{CO_2} ${t_{charcoal}}^{-1}$.[1] When evaluating the overall CO_2 balance of charcoal, it is also important to take into account that charcoal production could generate various by-products, such as pyrolysis gas and excess heat. Those by-products could be utilised for further application, e.g., electricity production, and offset emissions resulted from fossil fuels that would be used otherwise. This utilisation of by-products during charcoal production could improve the CO_2 balance negatively impacted by the indirect land use change. For example, Suopajärvi *et al.* [207] states that by-product utilisation could achieve overall offset of 1.079 t_{CO_2} ${t_{charcoal}}^{-1}$ used, Norgate *et al.* [165] calculated a similar value of 1.006 t_{CO_2} ${t_{charcoal}}^{-1}$ used. Overall in terms of the crude steel production, accounting for the emission off-set of by-products could achieve an additional reduction of 0.20–0.36 t_{CO_2} ${t_{CS}}^{-1}$ [165].

Reduction of ash content

Typically, ash content of biomass is much lower than of coal, but differences apply across the different types of feedstock. Woody-based biomass in particular is known for its low ash content, usually not exceeding 2 % (db) [37]. The ash content of wood chips is often even as low as 0.5 % (db) [230]. Upgrading woody-based biomass to charcoal increases the ash content, as devolatilisation occurs during the process. For example, MacPhee *et al.* [136] use charcoal of ash content of 1.91 and 4.30 % (db) for studying the quality of coke produced from coking coal blends with charcoal. The biggest share of ash in bio-based feedstock could be generally find in agricultural residues, which typically contain ash content of over 4 % (db). Ash content in wheat straw could be easily as high as 14 % (db) [37]. Realistically though, agricultural residues would not be considered for

[1] Assuming a charcoal of carbon content of 78.8 % [6].

the iron and steel application due to their low carbon content and unsuitable properties. In terms of coal-based fuels, the typical ash content is around 10 %, as shown previously in Table 2.1. For example, studies present values of ash content in coking coal of 8.2 % (ar) [9], in coke above 10 % (ar) [89] and in pulverised coal of 7.9 % (ar) [26]. As these values are on as received basis, converting them to dry basis (as done for biomass) would provide even higher ash content values.

The ash content in the coals results in slag formation and negatively impacts the productivity of the blast furnace [197]. Reducing the amount of ash input by fuel switching can hence positively impact the blast furnace performance. The reduction in operating cost as a result of using low ash coals is shown by Bennett & Fukushima [12]. As Nogami *et al.* [163] state that charcoal could even halve the slag generation of a conventional blast furnace, it could be expected that charcoal would reduce the operating cost of the blast furnace. The lower ash content of biomass also means that the inflow of combustible matter becomes larger, which could further improve the technical performance of the blast furnace.

Reduction in sulphur and phosphorus content

Substitution of coal-based fuels by bio-based fuels also results in a smaller amount of sulphur and phosphorus fed into the blast furnaces. Sulphur and phosphorus content in steel reduces its toughness (the amount of energy per unit volume that a material can absorb before fracturing) and ductility (the material's ability to plastically deform, e.g., to form a thin sheet by hammering or rolling). Sulphur could also impact its weldability (the material's ability to be welded). Therefore, reducing the input of these elements into the blast furnace is desired, especially as the desulphurisation in not able to remove all of the sulphur from steels. Instead, alloying with manganese is required to tie up the sulphur as manganese sulphide (MnS). Formation of MnS prevents severe embrittlement of steel by sulphur, but the presence of MnS precipitates still reduces the steel's ductility [14].

The majority of sulphur comes from coke, which can have sulphur content up to 0.7 % (db) [87]. Overall, about 3 kg of sulphur is supplied to the blast furnace via coal-based fuels for every tonne of hot metal produced.[1] Even though a certain amount of sulphur is desired for free cutting steels designed for machining and can be even added to improve machinability, most of the time the sulphur content in steel is reduced below 0.005 % when ductility is a priority. The sulphur content is sometimes reduced to even up to 0.001 % to

[1] Considering production of one tonne of hot metal requires 361.6 kg of coke of average sulphur content 0.7 % (db) and 154.8 kg of PCI of average sulphur content 0.3 % (db) [87, 106].

decrease the volume of MnS [193]. Sulphur is also undesired as it reacts with other added metals, such as titanium, and reduces the effect of their addition [193]. Sulphur content in woody biomass is between 0.01 and 0.1 wt% (db) [230], and hence fuel switching would significantly reduce the sulphur supply to the furnace. Phosphorus is even more difficult to be kept out of the steel than sulphur [10]. Hence bio-carbon fuels, containing roughly half of the phosphorus amount compared to a metallurgical coke [230], can help to control the phosphorus levels too. Feliciano-Bruzual [70] states that the hot metal value could increase by 32-45 % if low impurity content bio-based fuels are used, as their use would improve the quality of the hot metal. Therefore, apart from CO_2 emission reduction, switching to bio-based fuels presents an opportunity to improve the iron and steelmaking process.

Enhancement of coke reactivity

Studies highlight the positive impact of coking coal blends with charcoal on the reactivity of the final coke and hence its gasification performance within the blast furnace. For example, Hanrot *et al.* [93] observe that coke from charcoal has a higher reactivity than coke originated solely from coking coal, which as a result makes gasification temperature for CO formation occur at 100°C lower than for coke with no biomass blends. Similar observation is given in a more detailed work by Ng *et al.* [160], but the observed reduction in the gasification temperature was maximum 50°C. Only roughly 50°C reduction in the gasification temperature is also observed in a study by Suopajärvi *et al.* [208]. Unfortunately, the reasons why the study by Hanrot *et al.* [93] states much higher reduction in the gasification temperature the other studies are unclear. Overall it can be conclude that the enhancement of coke reactivity by addition of charcoal during cokemaking reduces the thermal reserve zone temperature of the blast furnace, leading to an overall energy savings. This will lead to a lower coke rate, resulting in a reduction in the total fuel consumption and hence potentially even further decrease of the CO_2 emissions.

Diverting from the use of scarce materials

One of the most important inputs during the iron and steelmaking process, coking coal, has been listed by the European Commission as one of the 27 critical raw materials [56]. By coking coal being included on the list means it is of a high supply-risk whilst, at the same time, being of a high economic importance for the European industry and value chains. Overall, the EU is highly import-dependant on coking coal as well as steam coal, with an import-consumption ratio 67 % and 70 %, respectively (2015 data) [101]. On top, import of coking coal to the EU is highly homogenised, as 75 % of coking coal is imported solely from USA and Australia [56]. Domac *et al.* [40] highlights that importing of fossil fuels is often associated with additional costs on top of the fuel cost just to maintain the supply channels, sometimes even of military means. Increasing the energy independence is hence very important to preserve energy security and reduce the EU's sensitivity to the current world affairs. Bioenergy could indeed play a key role in this as it can directly substitute the conventional fossil fuels used during the iron and steelmaking process. On top, prices of coking coal are highly volatile [23]. Therefore, it is the present author's belief that providing an alternative to coking coal via bioenergy deployment could be a strategic energy-use decision for the European iron and steel industry. Existing studies on biomass opportunities for iron and steel application across the different EU countries have not mentioned the benefits of increasing energy security and diversity at all. For example, the motivations within the study by Suopajärvi & Fabritius [205] are purely CO_2 reduction and increase in the use of renewable energy across Finland. Study by Wang *et al.* [237] for Sweden focuses only on the benefit of reducing CO_2 emissions. Hence coking coal being a critical material and the potential of biomass to reduce the dependence on it has not been sufficiently recognised in the literature studying the bioenergy integration into iron and steel from the whole system perspective and presents a gap in the approach.

2.3.3 Issues related to biomass utilisation within the process

Different properties to coal

One of the main issues related to biomass utilisation across an integrated steel plant is its different composition in comparison to the coal-based fuels. Table 2.4 presents an example of different bio-based products and their proximate and ultimate analysis values. Comparing these values with fossil fuel values presented earlier in Table 2.1, **low carbon content** and **high moisture and oxygen content** (calculated by difference) of biomass fuels can be observed. This results in **low energy content** of the bio-products when compared to fossil fuels. The net calorific value, sometimes referred to as lower heating value, is for bio-based fuels around 17 MJ kg^{-1}, where coal-based fuels range around 30 MJ kg^{-1}. The low calorific value means low energy density of the fuel and a requirement for its supply in high volumes to provide the required amount of energy and carbon. This will result an increase in the total fuel input, which might not be technically possible. It is therefore suspected by the present author that raw biomass would not be preferable, and biomass upgrading would be required to increase the energy content.

Despite the lower amount of ash in bio-products when compared to fossil fuels, some biomass types can have high levels of potassium and sodium (listed as **alkali metals**), and phosphorus. This can increase the amount of Na_2O, K_2O and P in the input [209]. Use of feedstock with low ash, and particularly of low alkali content, is important as alkali metals increase coke consumption and can cause scabs [206]. In addition, bio-based feedstock has generally **low fixed carbon content** and **high volatile matter** (between 70 and 86 wt% db) [230], which makes the evolution profile of biomass significantly different to coal. The selection of the feedstock for iron and steelmaking application should hence consider the requirements for those characteristic properties. Based the the values presented in Table 2.4, it can be assumed that the preferential feedstock would be generally limited to woody biomass only.

Table 2.4: Properties of different biomass types (ar = as received, daf = dry ash free). Data taken from Phyllis2 database [43].

	Raw feedstock		Pre-processed and thermo-chemically converted feedstock		
	Agr. residues Oat straw (#2816)	**Wood** Pine (#131)	**Wood Pellets** (#2808)	**Torrefied fuel** Beech (#2688)	**Charcoal** Oak wood (#3534)
Proximate analysis (ar %)					
Fixed carbon	12.48	14.10	16.44	21.49	63.57
Volatile matter	73.90	78.93	74.40	71.65	23.40
Ash	5.42	0.35	0.46	1.26	10.53
Moisture	8.20	6.61	8.70	5.60	2.50
Ultimate analysis (daf %)					
C	50.58	52.48	50.40	56.05	80.04
H	6.16	6.11	6.10	5.68	3.70
N	0.53	0.14	0.09	0.22	0.38
S	0.09	0.25	0.01	0.02	0.04
Heating value (MJ kg^{-1})					
LHV	16.02	17.58	16.78	19.09	
HHV	17.39	18.98	18.20	20.38	23.64

Despite choosing the appropriate feedstock and upgrading technique, the resulting bio-product would still be lacking the sufficient **mechanical strength**. Gupta [88] shows charcoal has a radial crushing strength of 30-40 kg cm^{-3}. Radial crushing strength of coke, on the other hand, is generally between 100-150 kg cm^{-3}. Study by MacPhee *et al.* [136] shows that CSR and CRI levels, i.e. post-reaction strength, of the final bio-cokes from charcoal blends are significantly lower than of traditional cokes. Therefore, considering 100 % fossil fuel substitution by biomass would not be possible and any whole system analysis should account for the technical restrictions.

Storage and transport

The difference in characteristics of bio-based fuels and coal-based fuels requires a different operation system to be set in place. Raw biomass, and even biomass upgraded to torrefied fuel or charcoal, has lower energy density than coal, which presents **additional costs** during transport, handling and storage. At the same time, bio-based products easily adsorb moisture [114] and so the transport and storage facilities have to be designed to prevent moisture re-absorption. Also, heat development from the biological and biochemical degradation as well as the possible chemical oxidation processes occurring during the storage are issues that have to be addressed. Lack of control measures, set to ensure suitable conditions for biomass storage are achieved, present risk of biomass **self-ignition** [230]. The prevention measures include, for example, natural convection of air through the biomass stored or temperature control across multiple points. All those aspects add to the overall cost of partial fuel switching. However, existing studies generally do not consider the on-site impact of handling different fuel on the overall costs of the final steel product [205, 237]. Sahu *et al.* [192] show that retrofitting a coal fired power plant for co-firing requires an investment cost ranging between USD 430 to USD 4000 per kW size plant, depending on the plant location, its type, etc. As far as the present author is aware, a study which would provide a similar estimate, but specifically for retrofitting an integrated steel plant for biomass utilisation, does not exist. This presents a limitation for estimating the CO_2 avoidance cost as there might be a chance that retrofitting of an integrated steel plant would be a highly capital intensive action.

Availability

Natural variation of biomass growth and possibilities for its harvesting impact the biomass supply and the corresponding costs. Sourcing biomass across the whole year is hence one of the challenges that an integrated steel plant would have to overcome in the case of bioenergy deployment. A consistent supply is achieved by using previously stored biomass or sourcing it from alternative locations. A specific case-study on supplying miscanthus to a biorefinery in Ohio by Sahoo & Mani [191] shows that biomass delivered directly from field to the plant is 21 % less expensive than biomass which is stored first. Sahoo & Mani [191] also point out that expanding the harvest window could reduce the biomass supply cost, as it allows longer time period during which biomass could be sourced from field to the plant directly. Annual fluctuations in biomass supply also occur due to various aspects like, for example, inconsistency in annual allowable cut or availability of the harvesting area [152]. Therefore, when modelling biomass supply chain, the seasonal and annual variations in its cost should be ideally considered.

Economic disadvantage of biomass over coal in iron and steel

Currently, without any carbon price, bio-based products are not economically competitive with coal-based fuels. Global coking coal prices range between 115 to 170 € t^{-1}, depending on the exact coal type, and are expected to drop to values between 82 and 122 € t^{-1} by 2022 [204]. On the other hand, prices of torrefied fuel range between 113–188 € t^{-1}, charcoal prices are even higher of 223–392 € t^{-1} [209]. The estimated CO_2 mitigation cost of replacing coke by charcoal is between 33–69 € ${t_{CO_2}}^{-1}$ [207]. Comparing this cost with today's price of CO_2 European Emission Allowances (as of 08/03/2019) of 22 € ${t_{CO_2}}^{-1}$ [22], one can see charcoal utilisation is far away from being economically attractive. Overall, feedstock cost takes the biggest share (54.0 %) during bio-products production, followed by capital cost (18.2 %). Increasing the economy of scale of the bio-product production could potentially reduce their cost by about 1 € GJ^{-1} [207], however, such cost reduction still would not be sufficient for the final bio-based products to be economically competitive with fossil fuels.

The economic viability of the fossil fuel substitution by bio-based products is different across locations. Feliciano-Bruzual [70] shows that the required carbon tax that would make bio-PCI economically competitive widely varies across countries. For example, Brazil would require carbon tax of around 42 € ${t_{CO_2}}^{-1}$. Below 60 € ${t_{CO_2}}^{-1}$ mark would be also China, USA and India. On the other hand, Germany, Japan and Russia would require carbon tax of over 100 € ${t_{CO_2}}^{-1}$ to make bio-based products economically appealing for their iron and steel industry. In addition, a different work estimates the required carbon tax for Australia between 84–102 € ${t_{CO_2}}^{-1}$ [164] and for Finland as 50 € ${t_{CO_2}}^{-1}$ [205]. It is suspected by the present author that those differences in carbon tax are due to different costs of fossil and bio-based fuels within each country and hence financial aspects related to bioenergy integration into iron and steel industry highly vary for each integrated steel plant. Based on the statement by Mousa *et al.* [155] that bio-product implementation will not happen without an introduction of policy instruments (such as carbon tax or CO_2 allowances), it is important for their successful implication to first assess the economic viability of bio-based fuels across different plants.

Chapter 3

Availability of biomass resources within the EU

One of the key aspects, which significantly impacts the feasibility of any bioenergy system, is the ability to supply sufficient amount of biomass resources at justifiable costs. This chapter, therefore, focuses on the first research question:

> *"Would the European iron and steel plants be able to source the sufficient amount of biomass and how would the fuel switching impact their steel production cost?"*

In order to answer this question, a detailed study on the biomass supply chain for each of the 30 integrated steel plants is performed. The spatially explicit approach, using the techno-economic *BeWhere EU* model deployed in the present study, allows tracking variation in the feedstock, biomass transport and biomass upgrading for each plant. Apart from obtaining an insight into how biomass could be sourced for each individual integrated steel plant, this chapter also includes discussion on emission savings and the plant-specific CO_2 avoidance costs.

The *BeWhere* model was developed initially at IIASA [107] and has been extensively adapted to study various problems related to bioenergy supply. The present author expands its application to study the iron and steel industry by modifying its core structure and developing an iron and steel specific module for it. The work presented in this chapter was produced under the supervision of Dr Sylvain Leduc, while participating at the Young Summer Scientist Programme 2017 at the International Institute for Applied Systems Analysis (IIASA). The content of this chapter is published in the Journal of Biomass & Bioenergy in Mandova *et al.* [140].

3.1 Bioenergy status in Europe

3.1.1 Current share in the EU energy mix

The share of renewable energy in the EU energy mix is currently on track to meet 20 % in 2020. In 2015, the renewable energy has reached 16.4 % of the primary energy production, to which bioenergy has contributed with a major share of 63.5 % (130.2 Mtoe y^{-1}) [1, 57], where only Cyprus, Ireland and Malta currently do not have bioenergy as the leading renewable energy source. Bioenergy is now also defined as the key energy source for reaching the following 2030 and 2050 renewable energy targets [113], therefore large increase in bioenergy demand across all sectors is expected over the next few decades.

The main consumption of biomass is currently for bioheat production. In 2015, the share of the gross final biomass consumption for bioheat equalled to 73.8 % (equivalent to 82.9 Mtoe). Use of biomass for transport or for production of bioelectricity was around 13 % each, as Figure 3.1 shows. The bioheat consumption was mainly within households (51.0 %), followed by the industry sector (25.8 %), which used biomass to support its primary activities [1]. However, the share of biomass use in the industry greatly varies across individual countries within the EU.

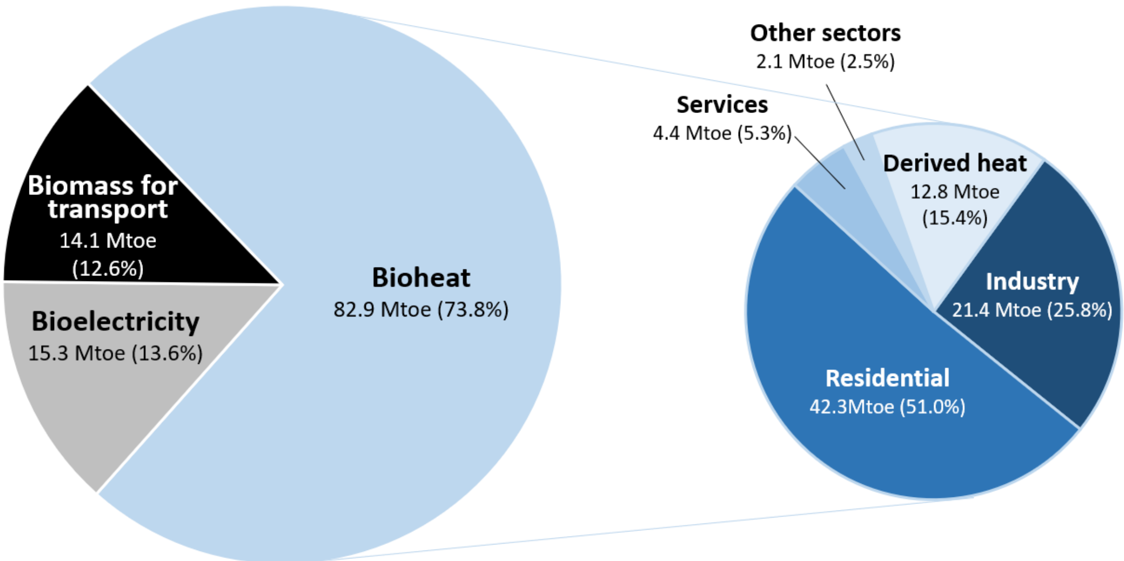


Figure 3.1: Gross final consumption of biomass across different sectors in the EU in 2015. Data from [1].

The leading bioenergy countries within the EU are Germany, France, Italy, Sweden and Finland, listed by their gross final bioenergy consumption. As Figure 3.2 shows, bioenergy development in Germany is ahead of all other countries, potentially due to the various renewable as well as biomass specific policies and measures implemented in the past 20 years (e.g., Kraft-Wärme-Kopplungs Modernisierungsgesetz) [102]. However, industrial use of bioenergy in Germany still accounts for only 14 % of the gross final bioenergy consumption. The biggest industrial consumers of bioenergy are Sweden (due to high demand from the pulp and paper industry) and Finland (due to high demand from the wood processing industry) [228].

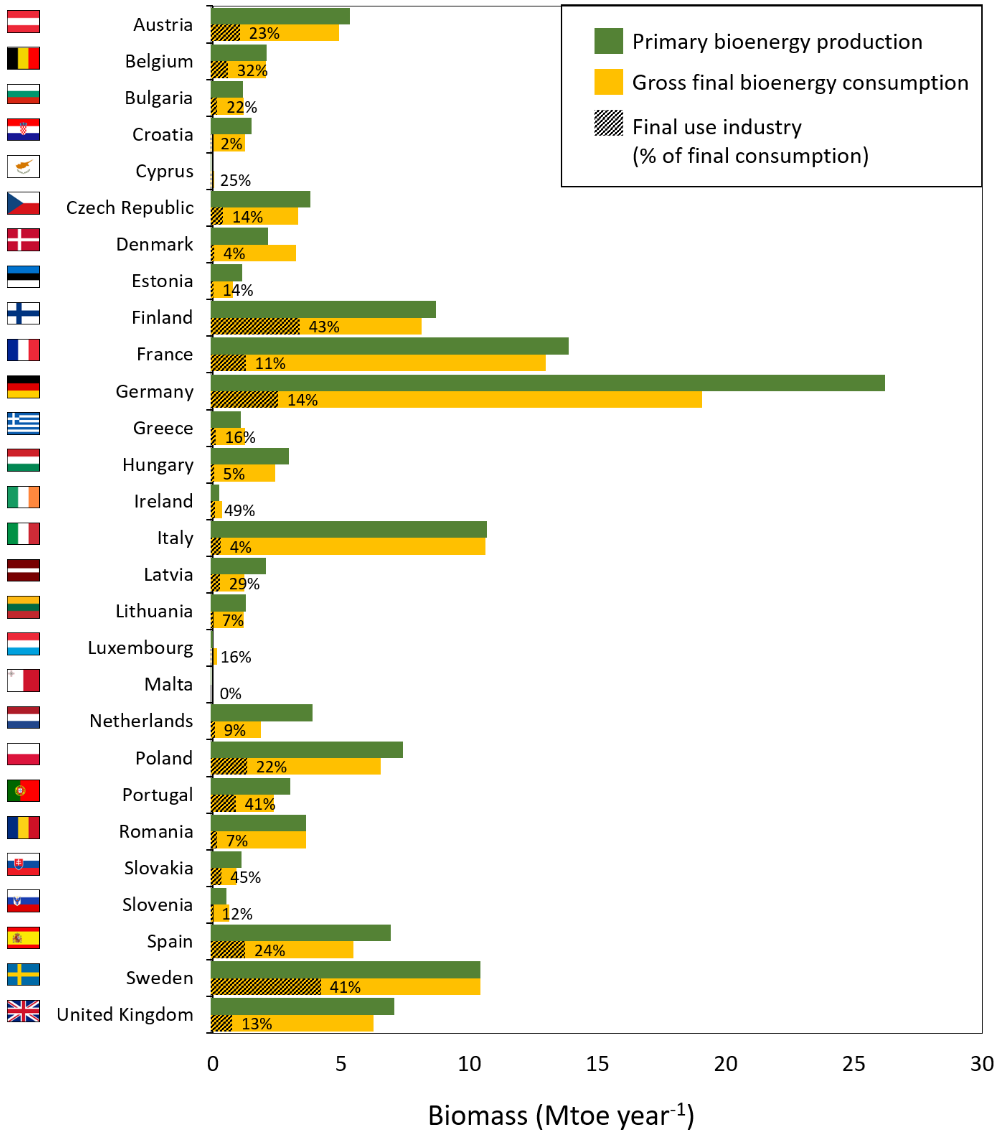


Figure 3.2: Primary biomass production and gross final energy consumption, including the industry share, in 2015. Data from [1].

3.1.2 Woody biomass potential in 2020, 2030 and 2050

The share of the total biomass resources (i.e., all crops, the corresponding harvested residues, grazed biomass, primary woody biomass and its by-products) used directly for bioenergy production is relatively small. As Figure 3.3 shows, only 19.13 % is used for energy production and most of this comes from forestry products. The rest is used for feed, food products and bio-materials [90]. The EU has approximately 5 % of the world's forests, and forestry products are used either as fuelwood or for sawnwood, veeners, and pulp and paper production [63]. Therefore, these industries would be affected the most by the increase of competition for woody biomass resources, if significant deployment of bioenergy within the European iron and steel industry takes place.

Quantifying the exact woody biomass potential in Europe is rather difficult due to the inevitable uncertainties within the applied methodologies. However, numerous estimates classified either as theoretical, technical, economic, implementation or sustainable potential exist, based on the applied assumptions and constraints. Representative examples of few studies is given in Table 3.1. Each of the listed potentials is important to fully understand the availability of biomass resources and the limitations for their use, leading to the best use of the limited biomass resources.

Table 3.1: Existing literature focusing on woody biomass potential within the EU.

Authors	Region	Type of biomass	Year	Potential type	Estimated amount (EJ y^{-1})
Verkerk *et al.* [233]	EU-27	Woody biomass	2010	Realisable	6.49
			2030	Realisable	5.43–7.80
Parikka [173]	Europe	Woody biomass	2003	Sustainable	4.0
S2Biom Project [35]	EU-28	Woody biomass	2020	Theoretical	8.53
IINAS, EFI and JR [108]	EU-28	Woody biomass	2010	Theoretical	6.33
			2020	Theoretical	7.64
			2030	Theoretical	7.75
Mantau *et al.* [142] EUwood	EU-27	Woody biomass	2010	Realisable	5.97
			2020	Realisable	5.91
			2030	Realisable	5.94
		Otherwood - second hand woody biomass (e.g., sawmill by-products, black liquor)	2010	Realisable	2.69
			2020	Realisable	3.23
			2030	Realisable	3.74
Wit & Faaij [245]	EU-27 & Ukraine	Lignocellulose bioenergy crops (willow, poplar, eucalyptus)	2010	Theoretical	4.4
			2020	Theoretical	7.2
			2030	Theoretical	9.5
		Forestry residue	2010	Theoretical	5.4

* Realisable potential is theoretical potential that is environmentally, technically and socially constrained.

Estimates of the realisable potential of woody biomass, i.e., the fraction of the theoretical potential that takes into consideration various environmental, technical and social

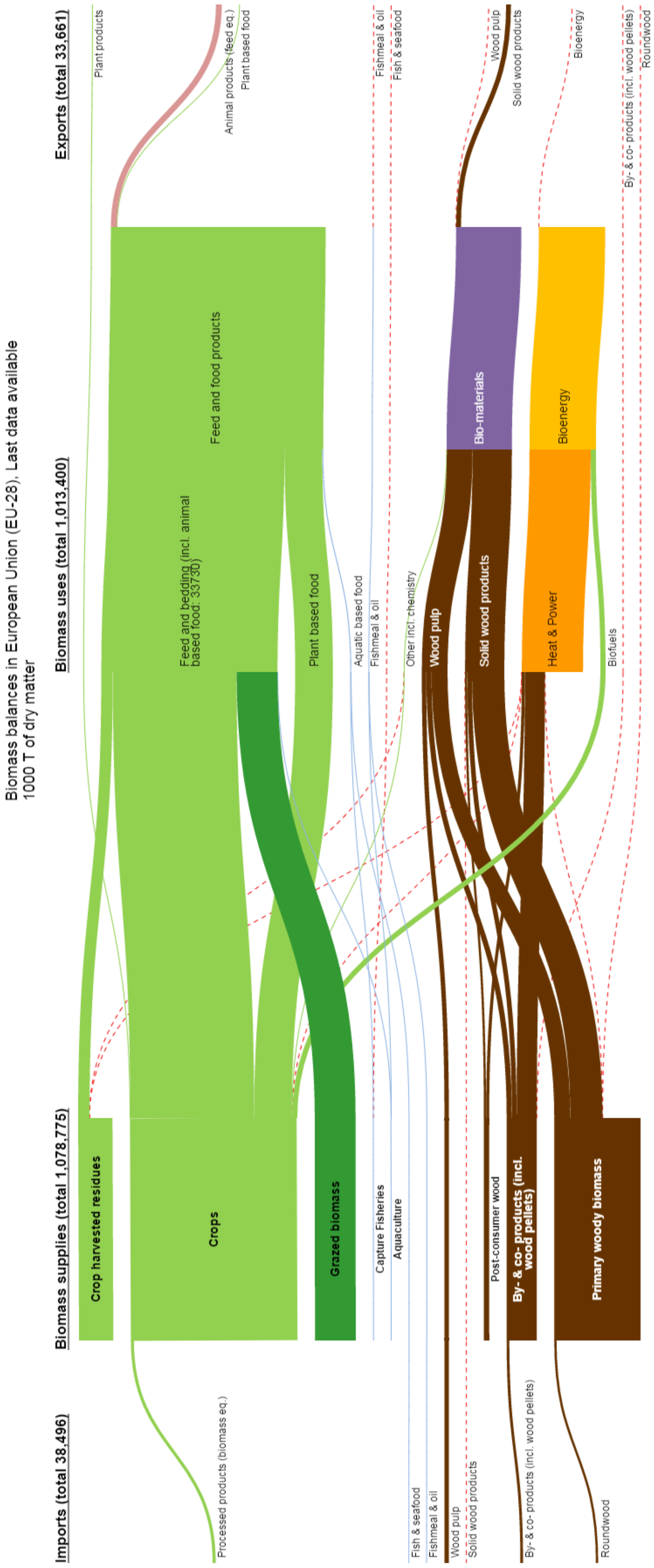


Figure 3.3: Sankey diagram of biomass supply and consumption across Europe in 2013. Figure from [90].

constraints, were around 6 EJ y^{-1} for 2010 [142, 233]. It is expected that the potential would rise only slightly by 2020 or 2030, as demonstrated by Mantau *et al.* [142] and Verkerk *et al.* [233]. However, a report prepared by IINAS, EFI and JR [108] indicates over 20 % increase in the theoretical potential by 2020 in comparison to 2010, and an additional small increase by 2030. Similarly, Dees *et al.* [35] in the S2Biom project listed a theoretical potential in 2020 of 8.53 EJ y^{-1} across all EU-28 countries. The Forest Europe report [75] also mentions that the amount of harvest wood is roughly 36 % less than the annual growth. The stagnation in the realisable potential, but increase in the theoretical potential, could therefore indicate an expected increase in the total woody biomass resources which extraction would be difficult. Such views are also given by Lauri *et al.* [127], who argue that the availability of biomass resources is a smaller barrier in comparison to accessibility of biomass resources, its transport cost and the resulting price. Mantau *et al.* [142] and Wit & Faaij [245] still expect an increase in woody biomass supply, but more due to an increase in the secondary wood streams and bioenergy crops. Therefore, the total amount of woody biomass produced in the EU could be expected to increase from now until 2020 and 2030, if the enhancement of woody biomass supply from other streams than forests takes place.

Demand for woody biomass within the EU is slightly more dominated by material use than energy use. In 2010, woody biomass used for material production equalled to 458 Mm^3 y^{-1} (3.99 EJ y^{-1}), for energy use to 346 Mm^3 y^{-1} (3.02 EJ y^{-1}) [142]. IRENA [113] identified a similar energy demand in 2010 of 2.80 EJ y^{-1}. This was split between the energy demand from industry and building, 0.97 and 1.84 EJ y^{-1}, respectively. Both studies expect a significant increase in the biomass demand for energy use in the near future. Mantau *et al.* [142] predicts as high as 65.6 % increase (to 573 Mm^3 y^{-1} $\approx$ 5.00 EJ y^{-1}) by 2020 and from then an additional 31.2 % (to 752 Mm^3 y^{-1} $\approx$ 6.56 EJ y^{-1}) by 2030. Similarly, material use should increase to 620 Mm^3 y^{-1} (5.41 EJ y^{-1}) [142]. IRENA's predictions about an increase of biomass use for energy has not been as high, in total 3.77 EJ y^{-1} in 2030 for the reference case and 4.14 EJ y^{-1} for the REmap 2030 [113]. Overall, woody biomass demand around 10 EJ y^{-1} could be expected by 2030. Based on the evaluation of the woody biomass potential by 2030, it can be expected that biomass from forests will have to be supported by other woody biomass streams to meet the increasing demand.

European biomass resources could be also extended by imports. Currently, most EU biomass demand is met domestically, and only 4.4 % of the gross inland consumption is imported from outside of the EU-28 countries [1]. This is despite the fact that some of the biggest biomass plants in the EU (e.g., Drax power station in the UK) import majority of their biomass from America. Importing biomass can create more cost-effective bioenergy applications than if solely domestic biomass is used. At the same time, importation can diversify biomass sourcing and trade dependency, e.g., due to seasonal variations [113]. Therefore, biomass trade within and outside the EU is required to meet the growing demand. However, all biomass, if grown domestically or imported from other countries, should be sourced sustainably to protect biodiversity, food prices and land ownership [113].

3.1.3 Woody biomass price

Geological, geographical, seasonal as well as political factors all impact biomass price. A report by Prislan *et al.* [180] shows high variation in wood fuel prices across countries in the EU. For example, wood pellets, packed in 15 kg sacks, can be is sold in Romania for 234 € t^{-1} or for as much as 349 € t^{-1} in Greece. It is important to note that these are prices for small-scale users. Large-scale users, to which iron and steel plants would belong, would source bio-products cheaper due to reasons such as lower quality standards or different contract possibilities [202]. Sikkema *et al.* [202] discuss the impact of the present players and support schemes on the pellet prices for large industry users. For example, Sikkema *et al.* [202] note that between 2007 and 2010, pellet prices were fluctuating between 110 and 145 € t^{-1} in Sweden, Denmark and the UK, with no similar trend between each other, and they were rather influenced by subsidies and CO_2 taxes imposed within the corresponding countries.

Focusing on the prices of raw woody biomass, high variation is also observed based on the part of a tree that the specific biomass comes from. Table 3.2 shows those differences for conifer and non-conifer trees across the EU countries. The differences in biomass costs between countries are also identified by Wit & Faaij [245]. Specifically Poland, Baltic States, Romania and Bulgaria are listed as regions with high potential and low costs, followed by France, Spain and Italy. The approach by Wit & Faaij [245] is, however, focusing on the supply potential, i.e., the amount of biomass possible to be supplied at the given price, not specifically on the average cost. For example, Wit & Faaij [245] identify that 60 % of lignocellulose crops (specifically poplar, willow and eucalyptus) could be supplied for under 2.5 € GJ^{-1}, particularly from Central and Eastern Europe and some areas in the south. Additional 30 % can be then sourced from 2.5 to 4 € GJ^{-1}. Specifically forestry residues then for between 2 and 4 € GJ^{-1} [245]. Those cost estimates by Wit & Faaij [245] make woody biomass competitive with fossil fuels in some places within the EU. However, biomass harvesting, transport and upgrading will further increase its supply cost, and hence subsidies or taxes imposed on fossil fuels would be required for any large-scale biomass deployment in an industry.

Table 3.2: Feedstock prices for different parts of tree and at different countries within the EU. Data from S2Biom project [35].

	Nonconifer trees (€ GJ^{-1})					Conifer trees (€ GJ^{-1})				
	Stumps from final fellings	Stemwood from final fellings	Stemwood from thinnings	Logging residues from final fellings	Logging residues from thinnings	Stumps from final fellings	Stemwood from final fellings	Stemwood from thinnings	Logging residues from final fellings	Logging residues from thinnings
Austria	4.07	2.87	3.44	3.44	4.01	4.59	4.23	4.27	5.05	6.03
Belgium	5.23	3.80	3.17	3.20	3.46	5.06	4.78	4.65	4.97	5.69
Bulgaria	3.42	2.04	2.20	0.39	0.44	3.66	3.24	2.99	4.24	5.01
Croatia	3.23	2.11	2.42	0.69	0.80	3.91	3.37	3.33	3.92	4.67
Cyprus	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Czech Republic	2.91	2.08	2.35	2.39	2.71	3.33	3.14	2.83	3.51	3.94
Denmark	4.31	3.17	4.13	3.85	4.70	5.62	5.93	0.00	5.50	0.00
Estonia	2.76	2.07	2.82	2.49	3.09	3.37	3.16	3.27	3.67	4.42
Finland	4.65	3.33	6.65	1.24	1.70	5.13	4.62	5.97	5.29	6.73
France	4.45	2.93	3.25	3.06	3.43	4.75	4.25	3.68	4.79	5.35
Germany	4.10	2.92	2.89	3.10	3.30	4.54	4.08	3.77	4.54	5.18
Greece	5.02	2.81	3.03	0.07	0.08	5.31	4.27	4.61	6.15	7.89
Hungary	2.87	1.89	2.17	1.84	2.09	3.43	3.06	2.90	3.36	3.89
Ireland	4.96	3.59	5.91	4.19	5.58	5.27	4.61	5.56	6.05	7.89
Italy	5.90	3.73	5.68	0.20	0.23	5.75	4.35	5.07	6.65	8.30
Latvia	2.72	2.06	2.95	2.32	2.88	3.11	2.93	3.20	3.37	4.09
Lithuania	2.50	1.87	2.30	2.24	2.66	3.04	2.89	2.94	3.25	3.86
Luxembourg	4.23	3.44	2.92	3.12	3.47	4.33	4.08	3.78	4.53	5.18
Malta	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Netherlands	4.66	3.45	2.82	3.10	2.91	4.60	4.09	3.58	4.68	5.25
Poland	2.56	1.80	2.08	2.11	2.41	3.12	2.90	2.73	3.09	3.51
Portugal	4.28	2.36	3.47	2.96	3.84	4.17	3.71	3.99	4.74	5.97
Romania	3.52	2.21	2.37	3.41	3.93	4.08	3.28	3.16	4.93	6.07
Slovakia	2.89	2.02	2.16	2.41	2.68	3.25	3.05	2.74	3.43	3.85
Slovenia	3.90	2.69	3.19	3.22	3.76	4.55	3.90	3.82	5.10	6.20
Spain	6.88	2.56	3.42	0.18	0.22	4.26	3.83	3.54	0.32	0.39
Sweden	4.74	3.50	6.60	2.57	3.43	5.46	4.93	5.74	5.81	7.28
United Kingdom	4.48	3.00	3.10	3.90	4.28	5.02	4.24	3.91	5.68	6.71

3.2 Mechanisms enhancing biomass use

3.2.1 Carbon tax and excise tax on energy

Environmental taxes and other market-based instruments are intended to reflect the external costs resulted from releasing GHG emissions [166]. It makes their emitters responsible for the damage that GHG emissions cause to the environment (such as damage to crops, loss of properties due to flooding, etc.) as well elevated health care costs (e.g., due to heat waves and droughts) [215]. At the same time, they could be a new source of governmental revenue and be classified as a tool to achieve the UN's Sustainable Development Goal number 7, aiming to reduce the carbon intensity of energy [226].

Across the EU countries, most of the emissions are taxed for road transport. However, tax on emissions emitted from non-road sectors is imposed only on a small percentage, even though the non-road sectors are responsible for the majority of the carbon emissions [166]. Coal, the biggest energy input within integrated steel plants, is untaxed in many EU countries and only four of the EU countries producing steel via BF-BOF route (Finland, France, Sweden and UK) have tax on coal above 5 € ${t_{CO_2}}^{-1}$ [166, 215]. Apart from the EU emission trading system, many countries have their own carbon price mechanism set alongside it, as shown in Figure 3.4. Setting an appropriate benchmark for taxes on energy use is difficult, as it requires evidence on the external costs, which are rarely available. OECD for its studies uses a value of 30 € ${t_{CO_2}}^{-1}$, which represents the low-end estimate of these external costs from CO_2 emissions only [166].

Carbon taxes are possibly good mechanisms, as a correlation between countries with higher carbon tax rates and lower carbon intensity of their GDP exists [166]. A carbon tax can impact carbon production at the source, however, they are still not reaching the intended goals for emission reduction. One of the reasons is that the current carbon tax is not enough to reflect even slightly the climate costs alone, as a better designed and targeted taxation should have the potential to be "a core element of cost-effective policy" [166]. Considerations related to increase in carbon taxes are linked with concerns about preserving competitiveness, equity and the influence of sectional and interest groups on the market behaviour. For example, Rivers & Schaufele [186] demonstrate that the decline in gasoline demand due to tax implications was more significant than it would have been, if an equivalent increase in the market price would occur. Therefore, an increase in product price due to taxation and market behaviour have different impact on the consumers, even though the final price change is the same.

3.2.2 EU Emission Trading System

Conversion towards renewables and significant emission reduction are encouraged in the EU using the Emission Trading System (EU-ETS). The EU-ETS is a key tool within the EU 2020 climate and energy package and focuses specifically on large-scale facilities producing in total 45% of the EU's GHG emissions. Its introduction in 2005 covered

Figure 3.4: The EU-ETS and national carbon tax imposed in Europe. The Netherlands is in a process of considering national carbon tax. Data from [215].

emissions produced from various industrial processes, including iron and steel plants, and capped then in total 2058 $Mt_{CO_2}\ y^{-1}$. The current phase 3, which started in 2013, is set up until 2020 and aims to reduce annually 38 Mt_{CO_2}, such that the overall emissions in those facilities decrease by 21 % by 2020, in comparison to 2005 level [53]. Some CO_2 allowances are allocated to industry for free, based on performance benchmarks. In the past few years, the allowances were very low due to their surplus on the market, which resulted in the criticism of the overall EU-ETS. Recently, the CO_2 allowances have experienced a large increase in the second quartile of 2018, currently reaching its maximum above 18 € $t_{CO_2}^{-1}$ (as of 17/8/2018) [22], as shown in Figure 3.5. The iron and steel sector has been included within the EU-ETS since the beginning [53], and the BF-BOF emission intensity has slightly dropped from 1.92 tCO_2 to 1.89 tCO_2 per tonne of crude steel between 2008 and 2014 [126]. However, a decrease in steel production capacities and even complete closure of some European integrated steel plants have also occurred since the EU-ETS has been introduced.

3.3 Existing energy system models

Integration of renewables into fossil dependent systems raises a large variety of questions about the additional costs, emission savings or technical feasibility. The importance to

Figure 3.5: Variation of the CO_2 allowance price within the EU-ETS since 2013. Data from [22].

understand the impact of renewables hence results in the development of many energy system models, summarised in the review article by Ringkjøb *et al.* [185]. As it is very hard to answer all the questions by one model, models are developed for specific study purposes. One of the ways to classify models is based on the approach that they describe the studied system. The **bottom-up** models focus primarily on describing the technologies used to meet the demand by the end-user. As it is technology focused approach, it is able to represent any technological advancements or competition within the system. **Top-down** approach models rather focus on the market behaviour and interactions across sectors or regions, but due to low amount of information on the technologies, they are not be able to represent any shift of preferences. Mai *et al.* [137] discusses the limitations of each when representing a reality in details. **Hybrid** models, which link bottom-up and top-down, allow to model the technology details with together with an overall behaviour of the economy. Combining the two approaches, however, increases the number of constraints and the model complexity, resulting in a high computing power requirement for running the model. An example of linking those is given by Böhringer & Rutherford [17].

Methods for finding the actual solution differs across the models. For example, **optimisation models** are built to maximise or minimise a stated quantity, which amount is defined using an objective function and constraints. Their calculation is hence heavily reliant on the input values. The problem can be then described via linear programming, mixed-integer linear programming, non-linear programming or using slightly untraditional heuristic optimisation [185]. **Equilibrium models**, on the other hand, work in terms of balancing supply and demand within the entire economy. In particular, partial equilibrium models then allow focus only on specific commodities and economic sectors [137]. A slightly different way of solving a studied problem is using **simulation**, where the whole system is described using algorithms and formulae. Simulations are commonly used for building scenarios and studying possibilities for different outcomes [137].

One of the main model characteristics is whether it makes decisions based on the future. In detail, **myopic** models make "short-sighted" decisions as they focus only on the current time horizon, e.g., the past couple of years out of a twenty year long time-frame. However, certain aspects such as emission reduction trajectory can still be taken into consideration within myopic models [137]. **Intertemporal** (sometimes listed as perfect foresight) models work more strategically than myopic models, as they take into consideration what might happen in the future. Their findings can then enable more strategic long-term investments [185].

Few of the most widely used models focusing on biomass include SWITCH (Solar, Wind, Transmission, Conventional generation and Hydroelectricity), IECM (Integrated Environment Control Model) and TIMES (The Integrated MARKAL-EFOM System). They are all bottom-up models, however, SWITCH and TIMES find a solution using optimisation, whereas IECM does this by simulation. In terms of studies related to biomass, their most recent utilisation has been particularly for studying BECCS technology deployment. In detail, SWITCH has been applied to study the emission reduction potential for BECCS deployment across the whole western part of North America [194], IECM for obtaining specific power plant calculations when considering BECCS [64] and TIMES to define bioenergy potential by 2050 in Sweden and France [76]. However, none of these models have previously focused on biomass availability for the iron and steel making applications. To answer the stated research question, the present work seeks an alternative model that has been either previously used to study biomass supply for an iron and steel industry or presents opportunities for its straight-forward modification for such purpose. The present work has identified the techno-economic *BeWhere* model as the most suitable for this study, as the model has been previously used to study various bioenergy systems and contains spatially explicit data on biomass resources in Europe.

3.4 *BeWhere EU* - iron & steel

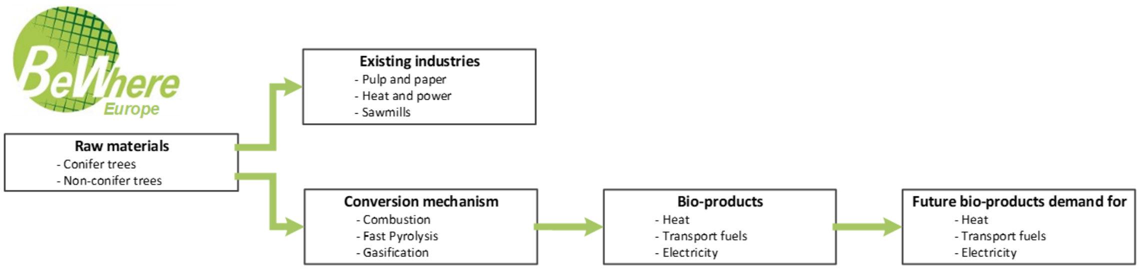
Existing *BeWhere* model

The *BeWhere* model was purposely built to find the optimal utilisation of biomass based on its availability, demand and cost [129]. The idea behind the model is to split the studied location into equally sized grid cells, each containing various location specific information important to define the biomass supply and demand within the region. Those grid cells are then matched to ensure supply meets the demand. The core of the model is defined in GAMS [148], however, all data are stored in Excel spreadsheets. The transfer of the data from Excel to GAMS is done using Python (resp. spyder) interface, which organises the data into an input file format suitable for GAMS. The model has been adapted multiple ways to study different locations and problems, for example electrification of buses in Sweden [253], impact of BECCS deployment on jobs in the US [174] or optimal location of renewable energy in the Alpine region [150]. The present work modified the *BeWhere Europe* model to study the potential of biomass in iron and steel sector.

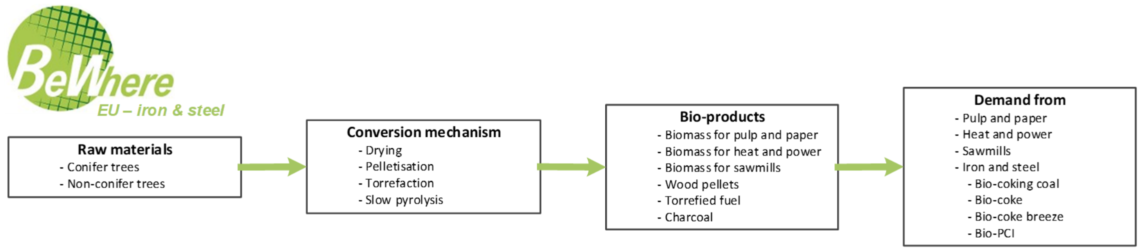
3.4.1 Methodology – Model modification for iron and steel applications

In the present work, the iron and steel industry was considered as an existing industry with multiple opportunities and restrictions for biomass substitution. The specifications of this industry therefore required structural change, by the present author, of the previously developed *BeWhere Europe* model (shown in Figure 3.6(a)) to make the model applicable. In detail, utilisation of the original *BeWhere Europe* model for studying iron and steel industry required extension of the previous conversion mechanisms list to include pelletisation, torrefaction and slow pyrolysis processes; bio-products such as wood pellets, torrefied fuel and charcoal and then using those bio-products in iron and steel industry, listed under existing industries. Following the previous structure, this would create a loop, difficult to define and solve using mixed-integer linear programming. Instead, artificial conversion mechanisms and bio-products[1] were introduced during the problem description for the existing industries, such that biomass demand from pulp and paper, heat and power and sawmills is met by their corresponding artificial bio-product. This made all industries follow the same – linear – structure, as demonstrated in Figure 3.6(b). To narrow down the focus of this study, only EU-28 countries were considered (in comparison to all European countries in the previous studies). At the same time, the focus was only on the current

[1]Technology described as "artificial" refers to a technology for which the resulting bio-product is the same as the input material, i.e., no additional costs or energy loss is considered during this conversion.



(a) Original *BeWhere Europe*



(b) Developed *BeWhere EU – iron & steel*

Figure 3.6: Modification of the *BeWhere Europe* model done in the present work.

demand for bio-products for heating, electricity, sawmills and pulp and paper production due to the lack of comparable data to be able to define their future biomass demand. The developed model in the present work is further referred to here as *BeWhere EU – iron & steel*.

The *BeWhere EU – iron & steel* still follows the key ideas of the *BeWhere Europe* (Figure 3.7), such as the grid-based structure (40 km × 40 km), objective function and biomass constraints. In detail, model objective is preserved to minimise the total cost of the system defined as:

$$\min \sum_{r=1}^{R} (c_r + e_r \times z) \,, \tag{3.1}$$

where c_r is a variable containing the cost of the whole biomass supply chain, biomass upgrading and fossil fuels used as reducing agents in iron and steel industry within country r; e_r is a variable summing all on-site emissions from the 30 studied integrated steel plants and z is the imposed tax on the produced CO_2 emissions. The *BeWhere EU – iron & steel* also conserved constraints defining: biomass availability, biomass trading within as well as outside of the EU-28 countries, meeting existing biomass demand, capacity of each pre-processing and upgrading plants. The listed biomass aspects of the *BeWhere Europe* model

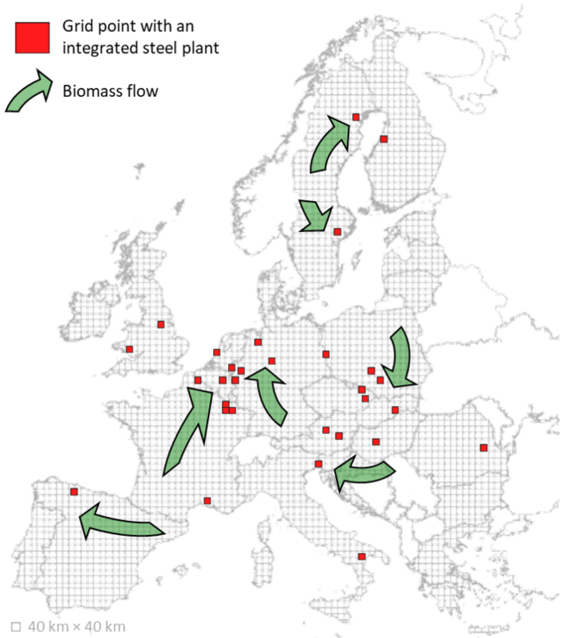


Figure 3.7: Demonstration of the idea behind the *BeWhere EU – iron & steel*

are already described in details in previous literature by Leduc [129] and Wetterlund [242]. Section 3.4.2 provides an overview of the spatially explicit input data used specifically for the present study and Section 3.4.3 describes the specific model development for the iron and steel industry.

3.4.2 Spatial-explicit input data

Biomass availability

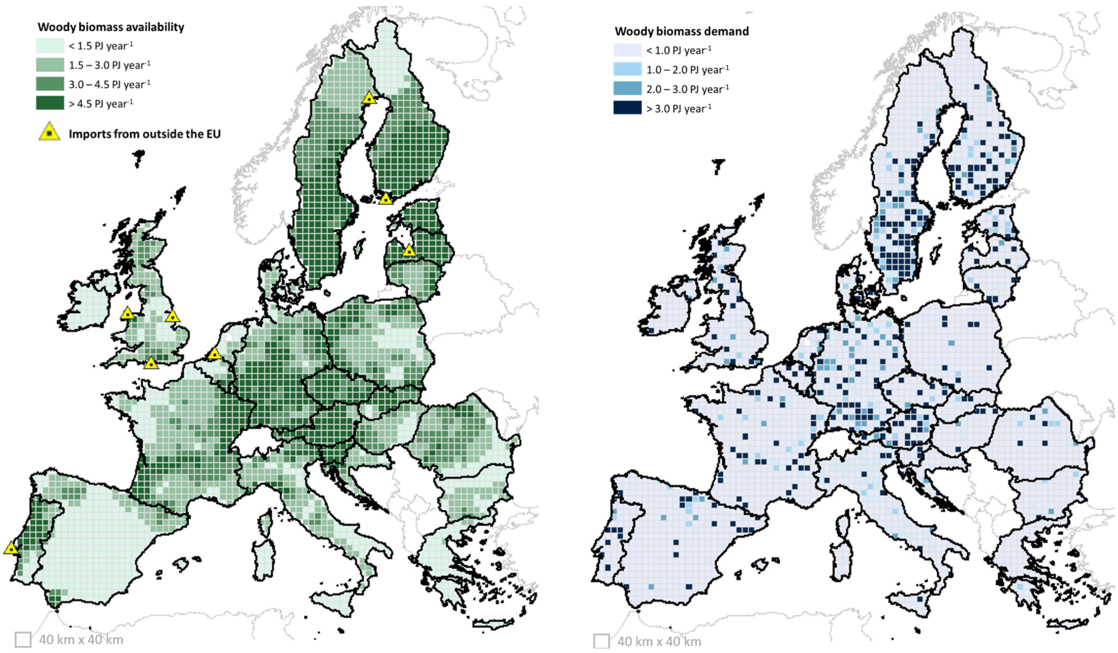
Available biomass is defined using S2Biom project data [35], which presents the theoretical potential of woody biomass in 2020. The dispersion of biomass within the EU is shown in Figure 3.8(a) and equals to the total of 8.5 EJ y^{-1}. To account for sustainability aspect related to biomass sourcing, this study considers only 70 % of the theoretical potential. The biomass availability data is further split between conifer and nonconifer trees as well as parts of the tree they are sourced from:

- Stumps from final fellings,
- Stemwood from final fellings and thinnings,
- Logging residues from final fellings and thinnings.

Country specific levels are provided in Table 3.3.

Table 3.3: Theoretical potential used for biomass availability summarised on country level, scaled within the *BeWhere EU* model by factor 0.7 to take into account the sustainability aspect. Data used from the S2Biom Project [35].

	Nonconifer trees (PJ y^{-1})			**Conifer trees** (PJ y^{-1})			**Sum** (PJ y^{-1})
	Stumps from final fellings	Stemwood from final fellings and thinnings	Logging residues from final fellings and thinnings	Stumps from final fellings	Stemwood from final fellings and thinnings	Logging residues from final fellings and thinnings	
Austria	6	44	14	61	197	70	392
Belgium	2	17	5	5	25	9	63
Bulgaria	10	39	19	3	23	16	109
Croatia	9	60	10	2	9	2	93
Cyprus	NA	NA	NA	NA	NA	NA	NA
Czech Republic	9	60	17	26	126	50	287
Denmark	1	8	2	3	17	7	38
Estonia	7	59	9	6	39	8	128
Finland	15	51	23	127	498	164	878
France	76	435	117	62	314	107	1112
Germany	56	335	96	95	421	169	1172
Greece	2	22	6	2	16	7	55
Hungary	18	85	29	3	13	6	154
Ireland	2	9	1	3	17	4	36
Italy	60	186	49	11	52	17	376
Latvia	19	76	25	18	65	19	220
Lithuania	9	35	10	13	44	17	129
Luxembourg	1	4	1	0	2	1	9
Malta	NA	NA	NA	NA	NA	NA	NA
Netherlands	1	8	1	1	7	2	20
Poland	22	110	22	77	272	93	596
Portugal	50	95	27	24	44	23	262
Romania	28	177	48	18	96	28	396
Slovakia	8	46	19	10	40	16	139
Slovenia	5	31	7	12	39	11	105
Spain	28	58	24	44	130	55	339
Sweden	29	106	27	143	621	193	1119
United Kingdom	21	95	29	18	114	20	298
Total EU-28	**494**	**2252**	**639**	**789**	**3240**	**1113**	**8527**



(a) Available woody biomass (b) Woody biomass demand

Figure 3.8: Availability and demand of woody biomass within the EU. Data from S2Biom project [35].

Biomass trade between other EU countries is considered at specific harbour locations. Similarly, biomass import from the outside of the EU is also allowed at one of the eight harbours marked in the Figure 3.8(a). No additional trade costs are assigned to the traded biomass, but biomass imported from the outside of the EU is assigned cost 20 % higher than the average biomass cost in the country to account for overseas transport cost, import taxes etc. National prices of each biomass type used in this study were already presented in Table 3.2 (Section 3.1.3) when discussing price ranges of woody biomass across the EU-28 countries.

Existing biomass demand

This study focuses on the existing biomass demand specifically from pulp and paper plants, sawmills as well as plants producing heat and power, as those were identified previously in Section 3.1.2 as the main industries which would experience an increase competition for the biomass resources in the case of biomass deployment across the integrated steel plants. Their existing demand is summarised in Table 3.4 and their dispersed sum is plotted in Figure 3.8(b). Data on the annual biomass demand from pulp and paper industry, sawmills and heat and power are obtained from CEPI database [28], FAO statistics [68] and Platts database [179], respectively. As this study is interested only in the available biomass resources, existing demand is met first before allocating biomass to the iron and steel plants. The future demand of those industries is not considered due to the lack of available and comparable data.

Table 3.4: Existing biomass demand from plants producing heat and power [179], pulp and paper [28] and sawmills [68].

	Heat and power (PJ y^{-1})	**Pulp and paper** (PJ y^{-1})	**Sawmills** (PJ y^{-1})	**Sum** (PJ y^{-1})
Austria	26.8	43.3	134.5	204.6
Belgium	80.2	22.1	24.1	126.4
Bulgaria	1.9	4.5	13.7	20.1
Croatia	2.1	9.0	23.2	34.3
Cyprus	0.0	0.0	0.0	0.0
Czech Republic	4.2	80.7	61.5	146.4
Denmark	66.7	4.9	5.6	77.2
Estonia	6.6	4.6	29.2	40.4
Finland	120.9	298.3	166.6	585.8
France	44.8	139.6	110.7	295.1
Germany	71.7	144.4	323.8	539.9
Greece	0.0	0.0	1.6	1.6
Hungary	12.7	8.6	7.6	28.9
Ireland	2.4	0.0	14.4	16.8
Italy	20.8	27.1	21.9	69.8
Latvia	3.0	0.0	57.0	60.0
Lithuania	5.5	0.0	20.5	26.0
Luxembourg	0.1	0.0	1.1	1.2
Malta	0.0	0.0	0.0	0.0
Netherlands	8.8	0.0	2.7	11.5
Poland	23.6	61.9	71.7	157.2
Portugal	9.0	32.2	16.7	57.9
Romania	2.3	5.5	81.8	89.6
Slovakia	0.3	8.5	23.1	31.9
Slovenia	0.4	7.6	10.7	18.7
Spain	24.5	124.5	36.5	185.5
Sweden	159.7	344.8	262.5	767.0
United Kingdom	328.4	39.1	52.6	420.1
Total EU-28	**1027.3**	**1411.1**	**1575.3**	**4013.7**

3.4.3 Iron and steel module

The purpose of the iron and steel module is to cover the modelling aspects essential for studying biomass use within integrated steel plants. Data availability and their confidentiality unfortunately present restrictions on the utilisation of plant specific details (such

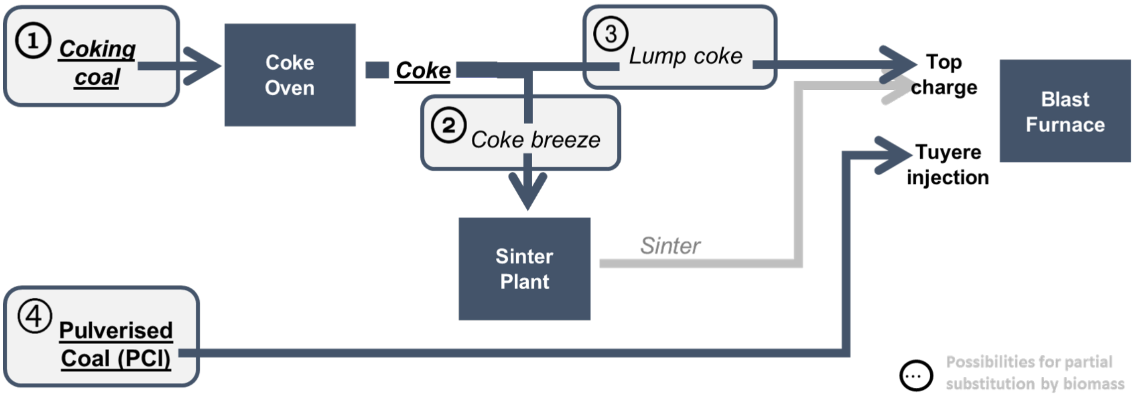


Figure 3.9: Demonstration of fossil fuel substitution possibilities by biomass.

the units presented on-site, specific amounts of different types of fossil fuels used, etc.), therefore it is assumed that each plant has the same structure as a typical Western European steel mill described in the IEAGHG report [106] and discussed earlier in Section 2.1.1 in Figure 2.1.

Across the integrated steel plant, there are typically four different coal-based fuels used: coking coal, lump coke, coke breeze and pulverised coal (PCI), as demonstrated in Figure 3.9. Each can be partially substituted by different bio-based fuels at different amounts. Table 3.5 lists the different types of coal and the input values used for the different types of fuel demand ($d_p^{CokingCoal}$, d_p^{Coke} and d_p^{PCI}), emissions ($e_p^{CokingCoal}$, e_p^{Coke} and e_p^{PCI}), and prices ($p_r^{CokingCoal}$, p_r^{Coke} and p_r^{PCI}) within a specific country r. Due to the restricted availability of country specific data on the prices and emissions of coal-based fuels, values listed in Table 3.5 are kept consistent for all studied plants.

Table 3.5: Potential for biomass substitution across an integrated steel plant, considering maximum substitution values found in the existing literature previously summarised in Table 2.3 in Section 2.3.1.

Fossil fuel	**Demand**[a] (GJ t_{CS}^{-1}) [106]	**CO_2 emissions**[b] (t_{CO_2} GJ^{-1}) [106]	**Fuel price**[c] (€ GJ^{-1}) [106]	**Bio-product**	**Max substitution**
1) Coking Coal	15.0	0.093	3.98	Charcoal	10% [209]
2) Coke breeze	1.5	0.111	5.35	Charcoal	10% [209]
3) Lump coke	9.4	0.111	5.35	Charcoal	10% [209]
4) PCI	4.6	0.096	3.17	Wood pellets	20% [237]
				Torrefied fuels	22% [237]
				Charcoal	100% [209]

[a] Used to estimate $d_p^{\cdot\cdot}$. Demand for coke breeze and lump coke is represented together as d_p^{Coke}.
[b] Used values for $e_r^{\cdot\cdot}$
[c] Used to estimate $p_r^{\cdot\cdot}$.

Table 3.6: Conversion efficiency of different technologies to final bio-products.

Technology t	Bioproduct y	Value $\eta_{p,t,y}$	Reference
Pelletisation	Wood pellets	1	
Torrefaction	Torrefied fuel	0.9	
Slow pyrolysis	Charcoal	0.65	[223]

The amount of bio-based fuels used by each plant is defined using variables $x_{p,t,y}^{CokingCoal}$, $x_{p,t,y}^{Coke}$ and $x_{p,t,y}^{PCI}$. Combination of biomass supplied within the country of the integrated steel plant, from other EU countries as well as outside of the EU is used to produce each bio-product ready to substitute the coal-based fuels, please see Equations (3.2). As upgrading biomass to final bio-products looses some energy, sum of raw biomass was multiplied by the corresponding energy retention efficiency of the conversion technology $\eta_{p,t,y}$, defined in Table 3.6.

$$x_{p,t,y}^{CokingCoal} = \eta_{p,t,y} \times \left(\sum_{s=1}^{S} \sum_{m=1}^{M} b_{s,m,p,t}^{domestic} + \sum_{h=1}^{H} \sum_{m=1}^{M} b_{h,m,p,t}^{imported} + \sum_{h=1}^{H} \sum_{m=1}^{M} b_{h,m,p,t}^{nonEU} \right) \tag{3.2a}$$

$$x_{p,t,y}^{Coke} = \eta_{p,t,y} \times \left(\sum_{s=1}^{S} \sum_{m=1}^{M} b_{s,m,p,t}^{domestic} + \sum_{h=1}^{H} \sum_{m=1}^{M} b_{h,m,p,t}^{imported} + \sum_{h=1}^{H} \sum_{m=1}^{M} b_{h,m,p,t}^{nonEU} \right) \tag{3.2b}$$

$$x_{p,t,y}^{PCI} = \eta_{p,t,y} \times \left(\sum_{s=1}^{S} \sum_{m=1}^{M} b_{s,m,p,t}^{domestic} + \sum_{h=1}^{H} \sum_{m=1}^{M} b_{h,m,p,t}^{imported} + \sum_{h=1}^{H} \sum_{m=1}^{M} b_{h,m,p,t}^{nonEU} \right) \tag{3.2c}$$

$$\forall \quad p \in \tilde{P}, \quad t \in \tilde{T}, \quad y \in \tilde{Y}$$

Demand for different types of fuels has to be satisfied for each plant p, either from fossil fuels, bio-based fuels or their combination, as described by Equations 3.3. As coke is product of coking coal, considering opportunity for simultaneously substituting both coking coal and coke by bio-based fuels would result in double accounting of the off-set emissions. Therefore, binary variable v_p is introduced such that demand for either coking coal or coke is satisfied. As PCI could be substituted by lower grade fuel, assumption that extra 10% of fuel would be required is applied when wood pellets and torrefied fuel is used [237]. This is incorporated in Equation 3.3c by introducing divisor w_t.

$$v_p \times d_p^{CokingCoal} = f_p^{CokingCoal} + \sum_{t=1}^{T}\sum_{y=1}^{Y} x_{p,t,y}^{CokingCoal} \tag{3.3a}$$

$$(1 - v_p) \times d_p^{Coke} = f_p^{Coke} + \sum_{t=1}^{T}\sum_{y=1}^{Y} x_{p,t,y}^{Coke} \tag{3.3b}$$

$$d_p^{PCI} = f_p^{PCI} + \sum_{t=1}^{T}\sum_{y=1}^{Y} \frac{x_{p,t,y}^{PCI}}{w_t} \tag{3.3c}$$

$$\forall \quad p \in \tilde{P}.$$

Maximum use of bio-based fuel at each plant due to technical aspects is defined using parameter $\bar{x}_{p,t}$ and a constraint below:

$$\bar{x}_{p,t} \times u_{p,t} \geq \sum_{s=1}^{S}\sum_{m=1}^{M} b_{s,m,p,t}^{domestic} + \sum_{h=1}^{H}\sum_{m=1}^{M} b_{h,m,p,t}^{imported} + \sum_{h=1}^{H}\sum_{m=1}^{M} b_{h,m,p,t}^{nonEU} \tag{3.4}$$

$$\forall \quad p \in \tilde{P}, \quad t \in \tilde{T}$$

The binary variable $u_{p,t}$, previously defined in *BeWhere* model, identifies whether a plant p is using biomass from technology t.

Total cost and emissions from fossil fuels used across the steel plant is represented using variables $c_r^{FossilSteel}$ and $e_r^{FossilSteel}$, defined on the regional level to preserve consistency within the model. Equations 3.5 and 3.6 show the formulation. Cost of biomass and its upgrading for iron and steel production purposes follows the same structure as previously developed in the *BeWhere Europe* model and hence omitted here.

$$\begin{aligned} c_r^{FossilSteel} =& \sum_{p=1}^{P} p_r^{CokingCoal} \times f_p^{CokingCoal} + \sum_{p=1}^{P} p_r^{Coke} \times f_p^{Coke} \\ &+ \sum_{p=1}^{} p_r^{PCI} \times f_p^{PCI} - \sum_{p=1}^{P} p_r^{ByProducts} \times d^{CokingCoal} \times v_p, \end{aligned} \tag{3.5}$$

$$\forall \quad r \in \tilde{R}$$

$$\begin{aligned} e_r^{FossilSteel} =& \sum_{p=1}^{P} e_r^{CokingCoal} \times f_p^{CokingCoal} + \sum_{p=1}^{P} e_r^{Coke} \times f_p^{Coke} \\ &+ \sum_{p=1}^{P} e_r^{PCI} \times f_p^{PCI} - \sum_{p=1}^{P} e_r^{ByProducts} \times d^{CokingCoal} \times v_p, \end{aligned} \tag{3.6}$$

$$\forall \quad r \in \tilde{R}$$

Generation of by-products from coke ovens' flue gases (i.e., electricity) is subtracted from the price and emissions of coking coal, such that the coking coal option is not disadvantaged due to generation of those by-products. This is achieved using parameter $p_r^{ByProducts}$ and $e_r^{ByProducts}$, representing the cost and emissions of coking coal input allocated to the by-products produced during coke-making.

The total cost of the whole system is then defined as before:

$$\begin{aligned} c_r =& c_r^{BiomassDomestic} + c_r^{BiomassImported} + c_r^{BiomassNonEU} \\ &+ c_r^{BiomassTransport} + c_r^{BioProduction} + c_r^{FossilSteel}, \qquad \forall \quad r \in \tilde{R} \end{aligned} \tag{3.7}$$

but extended by the variable defining the cost of fossil fuels used during iron and steel production, $c_r^{FossilSteel}$. It is important to note that only on-site emissions of the integrated steel plant are considered:

$$e_r = e_r^{FossilSteel}, \qquad \forall \quad r \in \tilde{R}. \tag{3.8}$$

Carbon price z between 0 and 200 € $\mathrm{t_{CO_2}}^{-1}$ is imposed on the emissions e_r to identify the additional cost related to bioenergy deployment at each integrated steel plant.

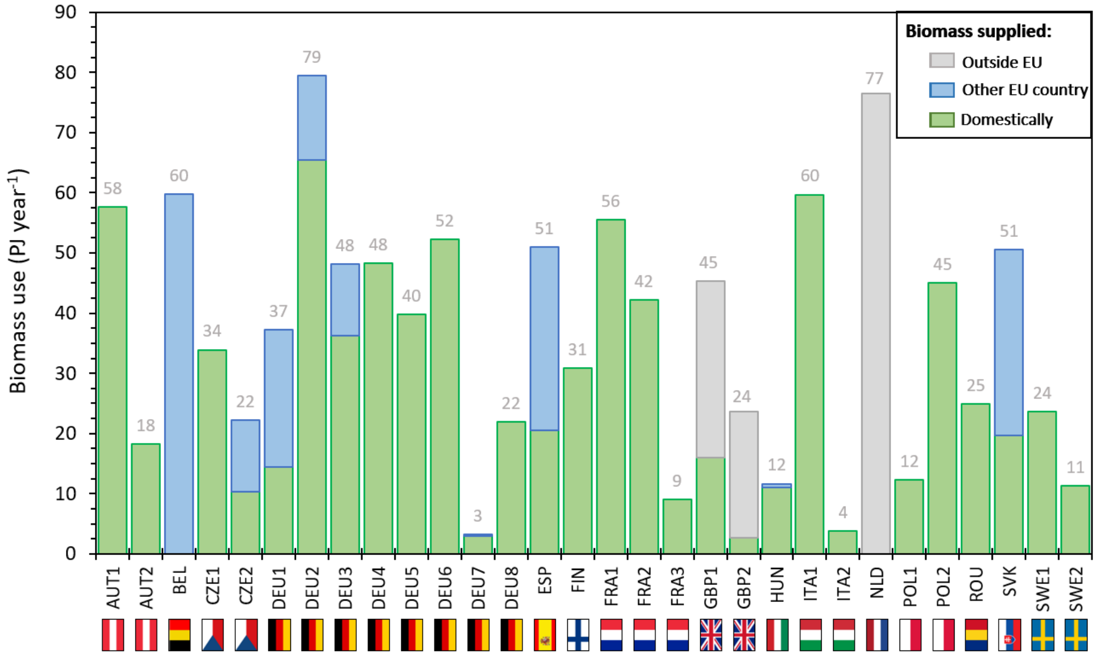
3.5 Results and discussion

3.5.1 The importance of international biomass trade

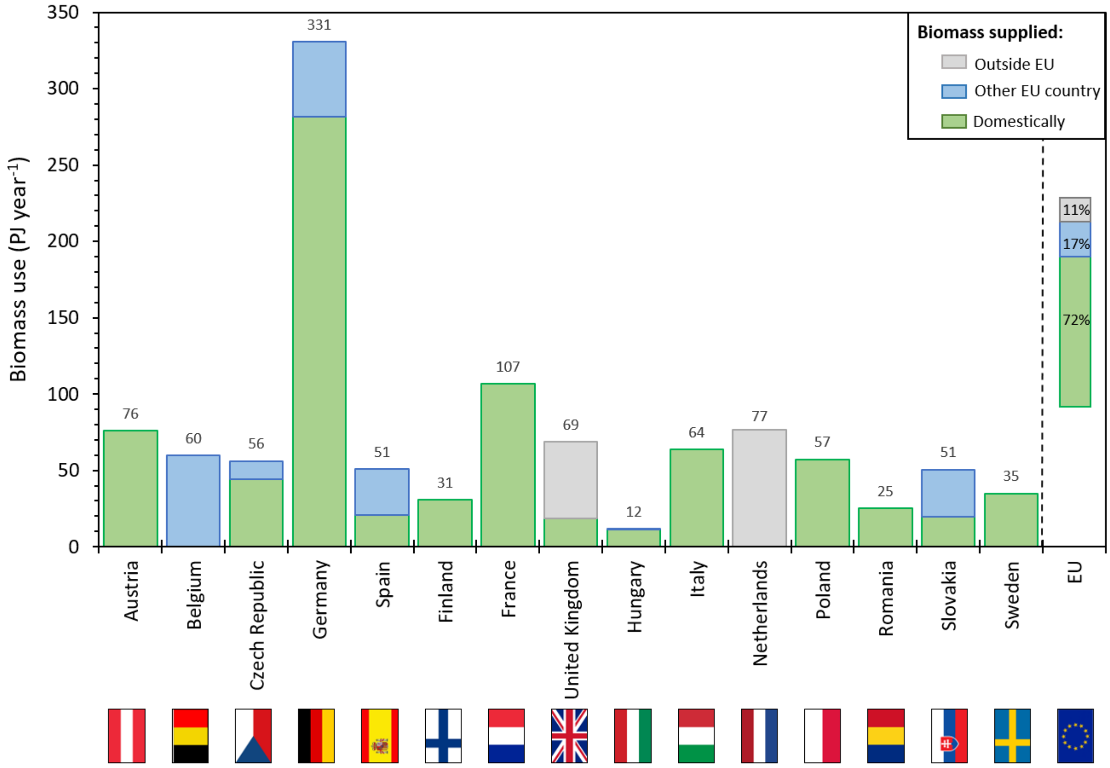
The ratio of biomass that each integrated steel plant could source domestically, rather than importing it from other EU/non-EU countries, depends on various aspects, such as biomass availability, feedstock cost as well as opportunities for biomass trade between countries. Figure 3.10 shows the results of the present work on the optimum biomass sourcing for each integrated steel plant, based on objective function set to minimise total cost of the studied system. The amount of biomass considered for each plant is equivalent to the maximum amount of fossil fuels that are technically-feasible to be substituted by bio-based products. The figure is broken down into two sub-figures to demonstrate the differences in biomass origin on plant as well as country level. The results indicate that a majority of biomass (72 %) would be supplied to the integrated steel plants directly from the country that each plant is located in. Biomass from the EU trade would then account for 17 % and biomass imports from the outside of the EU would account for the remaining 11 %. As the full biomass demand by the existing industries had to be met first before allocating any biomass to the integrated steel plants, it can be conclude that the techno-economic potential of bioenergy within the EU is sufficient to supply majority of biomass to the iron and steel plants domestically or from within the EU.

Focusing in detail on the obtained results, it can be observe that Austria, Germany, France, Italy and Poland are the countries with high potential to use domestic resources for the iron and steelmaking application. However, the IEA Bioenergy Tast report "Global wood pellet industry market and trade study" [217] from 2017, which reveals the current biomass situation (focusing specifically on wood pellets), shows that the use of purely domestic resources would be difficult. In detail, all of those countries are currently producing and/or consuming wood pellets of an amount which is only a small fraction of the estimated biomass demand by their integrated steel plants. For example, in 2015, Austria produced 1 Mt and consumed 0.85 Mt of wood pellets. The estimated total demand of 76 PJ y^{-1} (equivalent to energy content of approx. 4.4 Mt of pellets) by the two plants would hence be over four times the current use of the wood pellets within the whole country. The same applies for the other countries. It is important to note that the integrated steel plants would be using charcoal rather than wood pellets during maximum substitution. However, the charcoal production capacities in Europe are even smaller than for the wood pellet production. Therefore, despite the availability of biomass resources, minimal quadruple of the bio-products' production capacities would be required within the EU, such that the sufficient amount of bio-products could be sourced. This is highly unrealistic to happen in the near future and would impact the biomass market price equilibrium. Hence, only a fraction of the technically feasible substitution by biomass within the integrated steel plants should be expected to happen in reality.

International trade would be able to overcome the insufficient capacities of bio-product production in Europe, however, the potential demand would be multiple times bigger than it is currently traded. The results demonstrate that specifically plants in the Netherlands and Belgium would be reliant on the imported biomass in their full amounts. In detail, it is expected that the ArcelorMittal plant in Ghent (Belgium) would supply up to 60 PJ y^{-1} of raw biomass from other EU-28 countries. On the other hand, the Tata Steel plant in IJmuiden (Netherlands) would import up to 77 PJ y^{-1} of raw biomass from the outside of the EU. Such demand for biomass would, again, many times overshoot the current consumption as well as trade of woody biomass in their countries [217]. The other Tata Steel plants in the UK would also heavily rely on biomass imports from the non-European countries. However, the UK is slightly different in this case, as the maximum required amount of 69 PJ y^{-1} is equivalent to around 80 % of the amount of wood pellets that the UK currently consumes, due to large demand from biomass power stations (equivalent to



(a) Biomass sourcing - plant level



(b) Biomass sourcing - country level

Figure 3.10: Comparison of feedstock origin supplied to the corresponding plants at the maximum technically-feasible substitution rate.

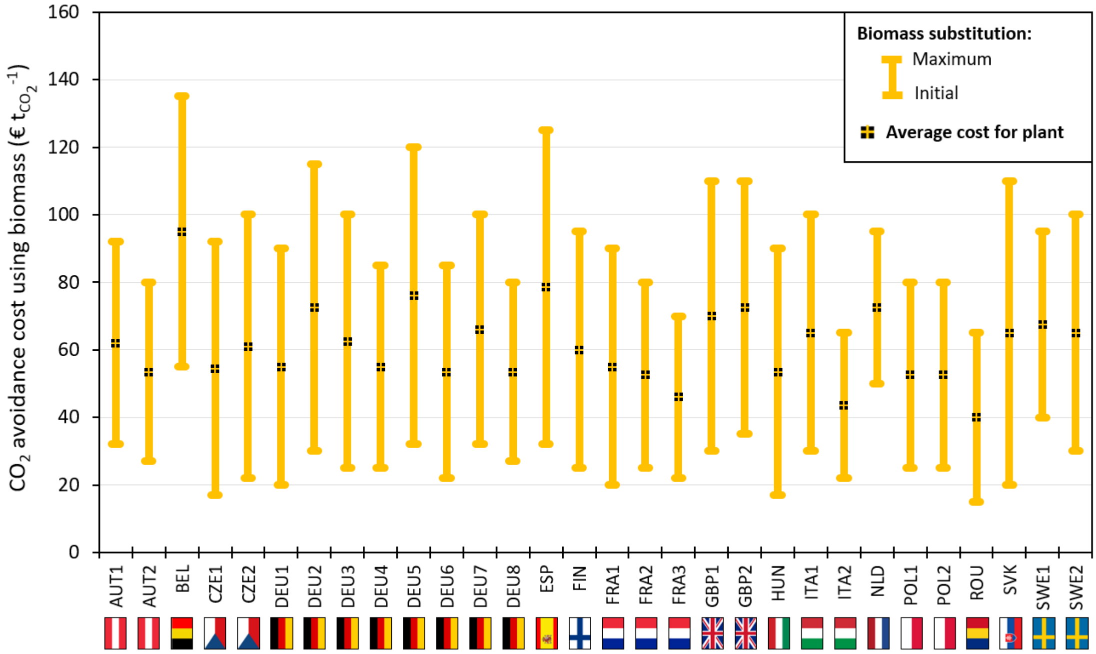
4.8 Mt y^{-1}, which are consuming wood pellets supplied dominantly from America) [217]. This makes the UK the only country in the EU, for which biomass imports for the iron and steel application would be of a similar scale that is already deployed.

Despite carefully assessing the biomass availability, the results of the present work are lacking sufficient assurance that the available biomass could be sourced sustainably. As mentioned in Section 3.4.2, this study considers 70 % of the theoretical bioenergy potential to account for the sustainability aspect related to its sourcing. Such uniform reduction, however, does not guarantee that the biomass supplied from the remaining amount would satisfy all the sustainability criteria. Similarly, in the case of biomass imports from the outside of the EU, the present results also do not guarantee that the imported biomass would be sustainably sourced. Indeed, one can argue that international biomass trade allows to grow feedstock at the most suitable locations with the highest yield, and overall producing a feedstock with the lowest emission intensity. This could in the end even offset the emissions resulting from the long distance transport of bulk biomass [45]. Such speculations are, however, hypothetical. Further research checking that the available biomass identified in the present work would satisfy all sustainability criteria, and hence be considered as carbon-neutral, is necessary.

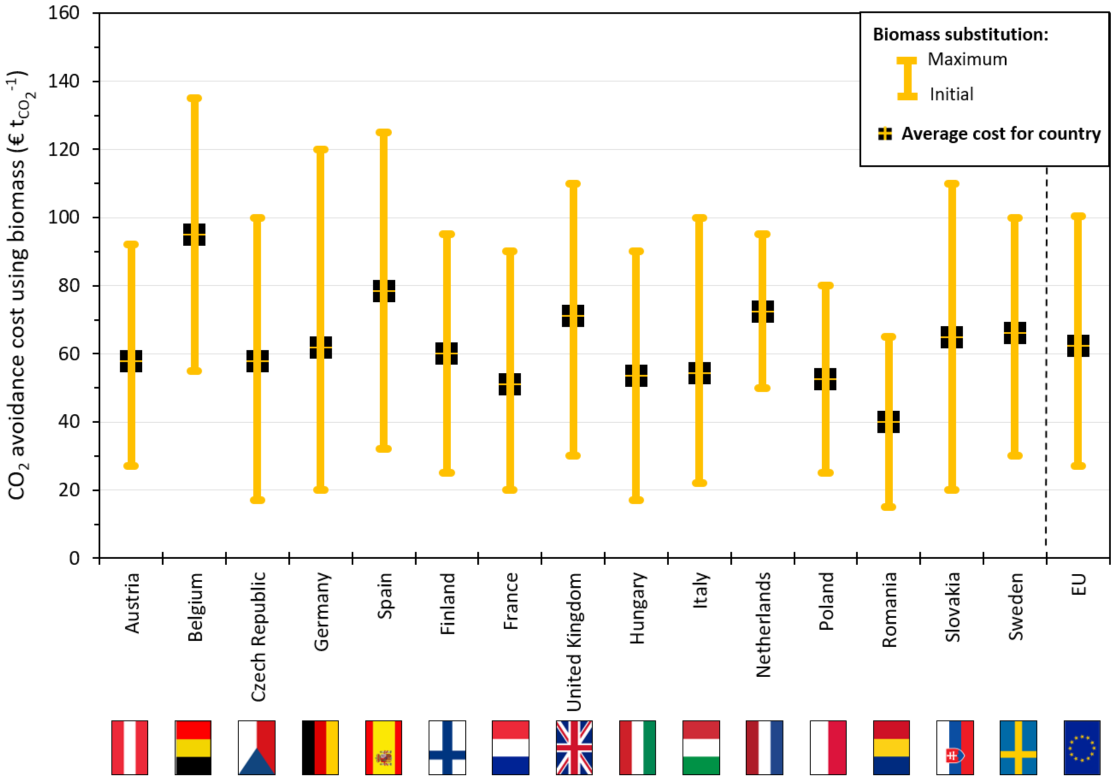
3.5.2 Competitiveness of biomass within the iron and steel sector

Despite the biomass trading opportunities discussed in the previous section, the use of alternative fuels is currently economically unappealing. The additional cost, expressed here as a CO_2 avoidance cost resulting from the biomass deployment, is presented in Figure 3.11 for each individual plant and country. As the cost of biomass supply is highly influenced by where the biomass is sourced from, variation in the supply cost for each integrated steel plant is observed. The figure is hence, apart from providing an average CO_2 avoidance cost for each plant, also demonstrating the variation in the biomass supply cost by providing the specific CO_2 avoidance cost at the minimum and maximum substitution. The high variation in the cost across the plants, and within each plant, reaffirms that the CO_2 avoidance using biomass would be of different costs, based on the plant and amount of CO_2 aimed to be reduce.

On average, the minimum CO_2 avoidance cost for iron and steel plants in Europe using bioenergy is 27 € $t_{CO_2}^{-1}$. The lowest cost is obtained for plants in Romania, Hungary and Czech Republic, starting from 15 € $t_{CO_2}^{-1}$. On the other hand, the highest cost is observed for the plant in Belgium, starting at 55 € $t_{CO_2}^{-1}$. Those listed minimal costs are indeed very high, particularly when compared to the 2017 average CO_2 allowance price within



(a) CO_2 avoidance cost - plant level



(b) CO_2 avoidance cost - country level

Figure 3.11: Comparison of CO_2 avoidance cost using biomass for different substitution range on plant level and country level.

the EU-ETS of 5 € ${t_{CO_2}}^{-1}$ [22]. However, recently the CO_2 allowance prices have been reaching peak values above 20 € ${t_{CO_2}}^{-1}$, as shown previously in Figure 3.5. Based on the values presented in Figure 3.11, the current CO_2 allowance price above 20 € ${t_{CO_2}}^{-1}$ makes bioenergy (in small amounts) economically appealing for some plants. Hence it can be expected that certain plants would seriously start considering its deployment in small amounts, if these CO_2 allowance prices sustain in the near future.

Utilisation of biomass for CO_2 avoidance in the iron and steel sector could be considered cost-effective when compared to the costs in other sectors, for example, power generation. In detail, Lüschen & Madlener [135] estimate that the CO_2 avoidance cost of using bioenergy for co-firing in Germany ranges between 25–32 € ${t_{CO_2}}^{-1}$. The results of the present work demonstrate that CO_2 avoidance cost for biomass in the iron and steel industry in Germany starts at 20 € ${t_{CO_2}}^{-1}$. Hence, the emission reduction using bioenergy in the iron and steel industry is of acceptable cost during the low levels of substitution. However, the iron and steel industry is completely different to the power industry and so the cost effectiveness of bioenergy in terms of the CO_2 reduction is difficult to compare. In detail, power generation produces electricity, which is used locally, whereas the iron and steel industry produces steel, which is traded globally. Therefore, even though the two industries have similar CO_2 avoidance cost (at least for the low levels of biomass use across the integrated steel plants), the corresponding increase in the production cost due to bioenergy deployment would have a more severe effect on the competitiveness of the integrated steel plants than on the power plants. Thus carbon price has to be carefully set to minimise the impact on the profitability of the iron and steel industry in the EU. Apart from profitability, a concern related to limited biomass resources and their efficient utilisation should be also raised here. In other words, biomass utilisation within the iron and steel industry should be preferential over power generation as, unlike steel production, electricity decarbonisation could be achieved by a wide selection of other renewable energy sources.

In total, biomass could reduce up to 76.8 Mt_{CO_2} y^{-1} across all integrated steel plants in the EU, equivalent to 40 % of the CO_2 emissions they produce annually. However, this would require imposing a carbon price up to 140 € ${t_{CO_2}}^{-1}$ for certain plants. Deployment of such carbon price would increase the hot rolled coil production cost by roughly 50 %, as shown in Figure 3.12. On the other hand, the reduction of 76.8 Mt_{CO_2} y^{-1} would be of average CO_2 avoidance cost of 62 € ${t_{CO_2}}^{-1}$ across the EU (Figure 3.11(b)). This would correspond to a steel production cost increase by only 52 € ${t_{HRC}}^{-1}$ (around 13 %). The lowest average CO_2 avoidance cost using bioenergy of 40 € ${t_{CO_2}}^{-1}$ is then observed for

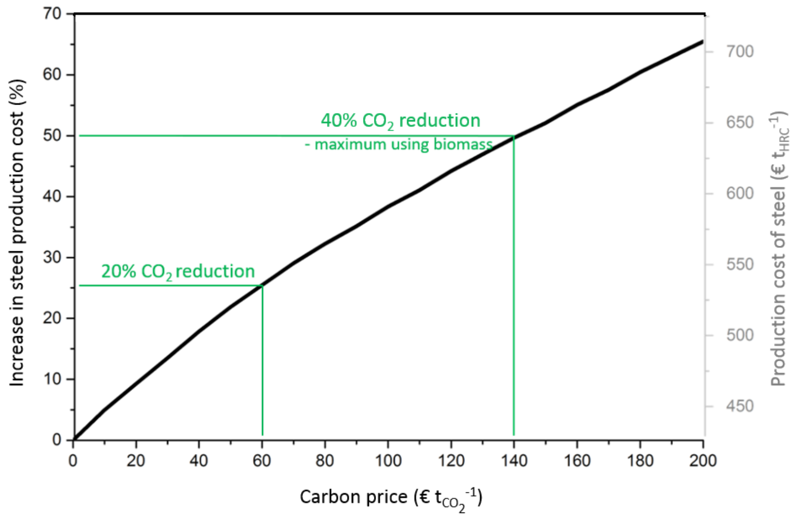


Figure 3.12: Impact of carbon price on steel production cost. Data on steel production cost obtained from [106]. Figure modified from the previous publication by the present author [140].

Romania and the highest of 96 € ${t_{CO_2}}^{-1}$ for Belgium. The significant differences in the values can be observed even across plants within the same country. For example, 40 % CO_2 reduction for the plant in Dunkerque (FRA1) would be of average CO_2 avoidance cost of 55 € ${t_{CO_2}}^{-1}$, for the plant in Fos-sur-Mer (FRA2) of 53 € ${t_{CO_2}}^{-1}$ and for the plant in Hagondange (FRA3) of 46 € ${t_{CO_2}}^{-1}$. This demonstrates the difficulties in setting the appropriate policy mechanisms across the whole EU to initiate CO_2 reduction, as each integrated steel plant is different and present different costs related to their CO_2 emission reduction.

A possible way to set the appropriate carbon price could be by studying the rate at which CO_2 reduction is achieved. Figure 3.13, representing the additional CO_2 reduction with every 10 € increase in the carbon price, shows that the achieved emission savings are not directly proportional to the carbon price imposed. Instead, a variable emission savings rate can be observed, occurring across two stages. This bimodal shape is a result of increasing economic viability of different bio-products – first domestically and then via trading opportunities. The highest rate of additional emission savings is observed at a carbon price of 40 € ${t_{CO_2}}^{-1}$. At this level, all plants, except the plants in Belgium and the Netherlands, would initiate biomass deployment. No other carbon price level would achieve an emission reduction as high, which makes 40 € ${t_{CO_2}}^{-1}$ the most cost-effective carbon price. The expected emission reduction across all countries at this carbon price would be of 23.9 Mt_{CO_2} y^{-1}, equivalent to 12.7%. If it is aimed to achieve emission reduction higher than 12.7 %, the second peak suggests imposing a carbon price of 100 € ${t_{CO_2}}^{-1}$, expecting a

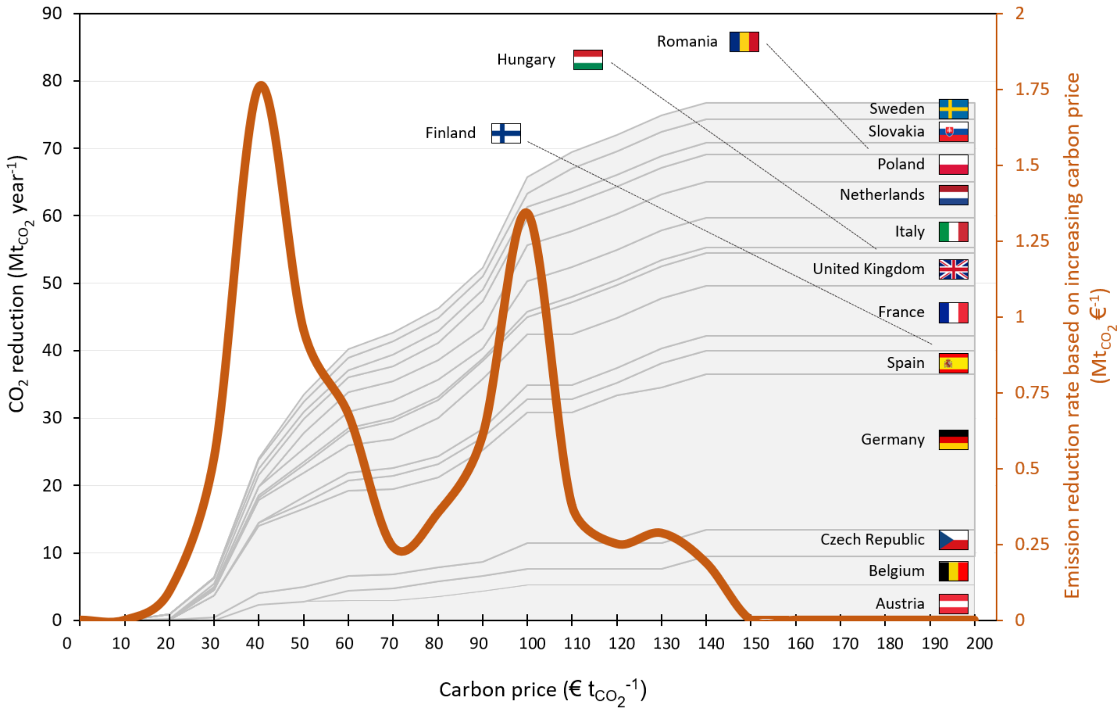


Figure 3.13: CO_2 emission reduction using biomass achieved from imposing different values of carbon price.

CO_2 emission offset of 65.7 Mt_{CO_2} y^{-1}. Therefore, the present author recommends setting carbon price at one of those two levels, as those carbon prices are the most cost-effective in terms of the CO_2 emission reduction they are expected to achieve. The carbon price of 40 € $t_{CO_2}^{-1}$ would be preferential over 100 € $t_{CO_2}^{-1}$, as it presents smaller impact on the steel production cost. Namely, the expected increase in the steel production cost would be approximately 16 % and 37 %, respectively (Figure 3.12). Overall, carbon price between 60 and 80 € $t_{CO_2}^{-1}$, and then more than 100 € $t_{CO_2}^{-1}$ would not be recommended, as their imposing would only increase the economic burden on the industry, whilst achieving a minimal additional CO_2 emission savings, in comparison to the previous levels.

The deployment of bioenergy within an integrated steel plant offers opportunities to reduce a certain amount of emissions occurring off-site, which reduces the overall CO_2 avoidance cost of biomass. Work by Suopajärvi *et al.* [207] shows that production of the bio-products could create by-products, such as electricity and heat, and hence off-set emissions that would be otherwise produced during their generation due to the use of fossil fuels. Their study first estimates CO_2 mitigation cost (without accounting for the by-products) for charcoal deployment within Finnish integrated steel plant of 33–69 € $t_{CO_2}^{-1}$. Those estimates are comparable to the range obtained by the present work of 25–95 € ${t_{CO_2}}^{-1}$, averaging 60 € ${t_{CO_2}}^{-1}$ (Figure 3.11). Suopajärvi *et al.* [207] then shows that the total CO_2 mitigation cost could be even lower, as much as 26-51 € ${t_{CO_2}}^{-1}$, if the off-setted emissions related to producing by-products are also taken into account. This is a very important finding as it demonstrates that an integrated approach could be more cost effective in reducing emissions that a segregated approach (which focuses only on offsetting CO_2 emissions on-site of an integrated steel plant) and hence should be encouraged.

3.5.3 The EU ETS as a tool for enhancement of biomass use

The present work indicates that bioenergy has the potential to significantly reduce emissions as well as decrease fossil fuel use by this industry, however it is lacking a sufficient economic viability. It is therefore important to discuss the role of the EU-ETS for enhancing biomass use within the iron and steel industry. The EU-ETS considers biomass as a zero-carbon fuel, so the EU-ETS does not account for any CO_2 emissions resulted from the biomass utilisation. The revised allocation of emission allowances post 2012 [44] combined the two independent benchmarks for blast furnace and basic oxygen furnace under a single hot metal benchmark. Bioenergy could be used at various parts of the process, and hence can help the integrated plants to meet specific benchmarks set specifically for cokemaking, sintermaking and now also for hot metal production as a whole. As the hot metal is the most emission intensive product across the whole iron and steel sector, which at the same time achieved the biggest emission allowance, combining blast furnace and basic oxygen furnace under one benchmark gives more credit to bioenergy use. This is because biomass can be mainly used by the blast furnace, so plants which have inefficient basic oxygen furnace now have an opportunity to offset emissions using biomass at the most suitable process unit within the plant, which would result in efficient use of the available resources. For the best bioenergy integration under the EU-ETS it could be argued that all three stages: cokemaking, sintermaking and hot metal production, should be under one benchmark (if they are all present on one site), so that biomass is used where it is the most suitable based on its properties, rather than where emission reduction is required.

Overall the EU-ETS as a policy tool might not be the best way to introduce bioenergy into the iron and steel sector. Iron and steel is highly CO_2 intensive, but it is also internationally traded so any additional costs (either due to emissions or purchasing alternative fuels) could impact its competitiveness, as mentioned earlier. Even though some studies have argued that the EU-ETS should not significantly impact the productivity and competitiveness of this industry [36], the EU-ETS might not be the best way to increase bioenergy share in this sector. In addition, work by Schwaiger *et al.* [198] on biofuels also points out that the price fluctuations of the allowances does encourage long term investments into bioenergy technologies in general. Therefore, alternative instruments such as subsidies or tax reliefs might be better incentives. These should be ideally targeting specific plants, rather than all of them the same way, as each plant has a unique opportunity for the biomass substitution. Only then, successful bioenergy integration into this industry, which also benefits the local economy and ensures sustainable biomass supply, could be achieved.

3.6 Chapter summary

Using the *BeWhere EU – iron & steel* model, this chapter evaluates the availability of biomass resources within the EU for their utilisation across the 30 currently operating integrated steel plants. The results demonstrate that the main barriers for the biomass deployment are costs and insufficient facilities within the EU to produce the required amount of suitable bio-products, not necessary the availability of biomass itself. Hence first, sufficient biomass supply chain in Europe is necessary to be established before high level of bioenergy deployment across the integrated steel plants is seriously considered. Strong international biomass trade would be also necessary to achieve the full technically-feasible biomass deployment.

Opportunities for bioenergy use across each individual integrated steel plant can be evaluated either based on: the availability of domestic biomass resources for such application or the feasibility to supply cheap bio-products from other countries. Germany, Austria, France, Finland, Italy, Poland and Sweden present a potential to supply sufficient amount of domestic biomass for the iron and steel making purposes. On the other hand, Romania, Hungary and the Czech Republic have the advantage to supply the feedstock cheaper than any other countries. Therefore, it is hard to determine which countries have the best opportunities, as such conclusion depends on multiple factors, including the decarbonisation technology preference of the plant operators, an aspect not included in this study. Overall though, biomass deployment within any integrated steel plant would require policy incentive, as it is currently economically unjustifiable. Depending on the size of such support, biomass within the iron and steel industry in the EU has a potential to offset up to 76.8 Mt_{CO_2} y^{-1} (equivalent to 40 % of the plants' CO_2 emissions). However, such maximum technically-feasible deployment of biomass within the plants is not the most cost-effective use of the limited biomass resources. The results rather indicate that setting carbon price of 40 € ${t_{CO_2}}^{-1}$, with expected emission reduction of 23.9 Mt_{CO_2} y^{-1}

(12.7 %), would achieve the greatest emission savings when compared to the costs. However, imposing the carbon price of 40 € ${t_{CO_2}}^{-1}$ would increase the average steel production cost by 16 %, which would significantly impact the competitiveness of the European steel on the global market.

Chapter 4

Pathway towards carbon neutrality

Bioenergy deployment within the iron and steel industry presents significant, but not sufficient, CO_2 emission reduction opportunity. To answer the second research question:

> *"Does bioenergy have the potential to be also a long-term emission reduction strategy and have an important role in the total decarbonisation of the European iron and steel plants?"*

this chapter explores the possibility to achieve carbon-neutrality via biomass co-application with CCS (bio-CCS). Using the techno-economic *BeWhere EU – iron & steel* model, described in detail previously in Chapter 3, this work reveals the feasibility of bio-CCS across the European integrated steel plants by developing a CCS module.

The work presented in this chapter has been performed at IIASA under the supervision of Dr Piera Patrizio and Dr Sylvain Leduc, initiated from receiving additional funding as part of the Peccei Award. The presented methodology for modelling CCS/bio-CCS deployment across the iron and steel industry has been developed by the present author and the key concepts have been submitted for publication at the GHGT-14 conference proceedings in Mandova *et al.* [139]. The key findings are also summarised and published in the Journal of Cleaner Production in Mandova *et al.* [141].

4.1 Possibilities for enhancing the emission reduction potential

4.1.1 Hybrid approach for biomass

The amount of CO_2 that can be offset by pure bioenergy deployment is insufficient, particularly when aiming to achieve the EU's long-term CO_2 reduction targets of over 80 %, compared to 1990 levels [52]. The limited emission reduction potential is one of the reasons that define bioenergy use in the iron and steel industry as a short to medium-term, rather than a long-term, strategy. However, the EU's long-term targets rely on deployment of cutting-edge technologies, which are still far away from their large-scale application. One of the options to increase the bioenergy emission reduction potential is its simultaneous deployment with other low carbon technologies, which technology readiness level has already passed its commercialisation state, but the technologies on its own are not able to completely decarbonise the process. A technology that offers an excellent pair-up opportunity with bioenergy is carbon capture and storage (CCS).

Bio-CCS (in certain applications often written as BECCS) is one of the negative emission technologies (NETs). Scientists have started to pay significant attention to the NETs due to their ability to remove CO_2 from the atmosphere and durably storing it in geological, terrestrial and ocean reservoirs, or in products [112]. Apart from bio-CCS, NETs include large-scale afforestation, direct air capture, soil carbon sequestration, biochar formation and enhanced weathering [78]. However, bio-CCS/BECCS and afforestation are by far the most discussed technologies [112].

Previously, concerns have been raised about the impact of bio-CCS/BECCS on the environment in terms of freshwater, integrity of ecosystems, large-scale changes to land areas or shifts in flows of nitrogen and phosphorus. A study by Heck *et al.* [95] concludes that the global carbon storage from bio-CCS/BECCS applications should be smaller than 100 Mt of carbon per year, to prevent risking the impact on the listed aspects. Fuss *et al.* [77] also discuss the uncertainty in the response of the natural land and ocean carbon sinks to the CO_2 storage and the financing prospects of bio-CCS/BECCS in general, as its deployment is generally presenting only an economic burden for any plant that is considering it. Currently, the bio-CCS/BECCS is not sufficiently supported by the public and relevant policies are not set yet for such technology. However, it is widely anticipated that under careful management of supply chain, bio-CCS/BECCS can deliver net negative emissions [64] and further efforts are required to overcome the listed concerns and negative impacts of any bio-CCS/BECCS application.

4.1.2 Bio-CCS deployment within the iron and steel industry

The CCS, on its own, is one of the key decarbonisation technologies discussed for the iron and steel sector as well as for an industry in general. A join report by IEA and UNIDO [104] states that CCS could reduce the emissions within the industry sector by up to 4.0 Gt_{CO_2} y^{-1} by 2050. However, this means its large-scale deployment, where CCS would be attached to 20 to 40 % of all industrial plants [104]. Multiple studies have already focused on the application of CCS for the iron and steel plants. For example, findings obtained by Ho *et al.* [97] and Wiley *et al.* [244] provide an insight into the most suitable flue gas for CO_2 capture. Kuramochi *et al.* [124], on the other hand, discuss the benefits of CO_2 avoidance via CCS over other technologies. The first fully commercial CO_2 capture facility for the iron and steel industry is already operating in Abu Dhabi, even though it is deployed for the DRI-EAF steel production route. Annually, 800 kt_{CO_2} is captured and used in the nearby oil reserves for enhanced oil recovery [85]. It is important to be aware that the CO_2 capture installation within an integrated steel plant is slightly more challenging than for a power plant. First, integrated steel plants have multiple sources of CO_2 generation points, each of a different CO_2 concentration in the corresponding flue gas. Second, the steel plants are more likely to loose their competitive advantage by CCS deployment than power plants, as steel products are traded on an international market [104]. However, Quader *et al.* [181] in their review work conclude that implementation of CCS is still an effective way for CO_2 avoidance. Surprisingly though, none of the listed studies on CCS within the iron and steel industry have considered a case where CCS would be deployed together with biomass.

Bio-CCS is a combination of two CO_2 reduction technologies, which also use two different approaches for the CO_2 accounting. This makes the CO_2 saving estimates of the bio-CCS within an integrated steel plant less straight forward than when bioenergy or CCS are used on their own. In detail, during biomass growth, biomass extracts CO_2 from the atmosphere. During its utilisation, CO_2 is released back to the atmosphere. As it is assumed that no more CO_2 has been created during the biomass production, the released CO_2 is classified as carbon neutral. The CCS, on the other hand, avoids CO_2 being released into the atmosphere by capturing it and storing it underground. As the CO_2 capture process is energy intensive, the energy demand by the plant increases. This result in an additional CO_2 emissions produced during the process. Defining the net CO_2 balance when bio-CCS is deployed hence requires care.

Taking into account those differences in the CO_2 accounting, bio-CCS offers an opportunity for iron and steelmaking process to become carbon neutral as Figure 4.1 demon-

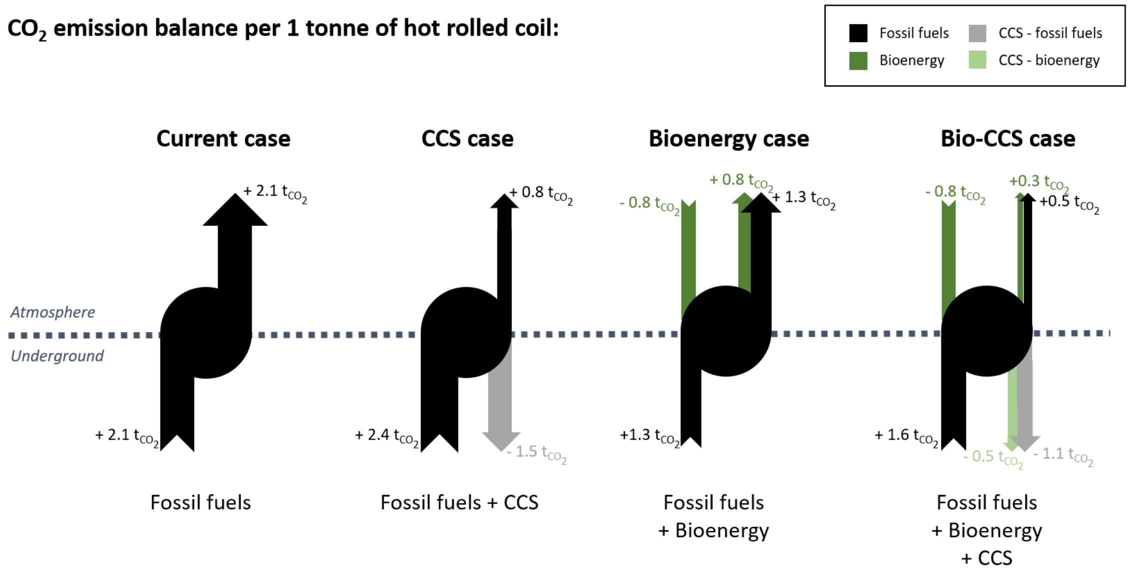


Figure 4.1: CO_2 emission balance for producing one tonne of hot rolled coil via BF-BOF route. Providing details of the CO_2 flow when CCS, bio-products and bio-CCS are deployed.

strates. Currently, around 2.1 t_{CO_2} is released into the atmosphere with every tonne of hot rolled coil produced from the European integrated steel plants [106]. The techno-economic IEAGHG report on iron and steel [106] estimates a maximum realistic CO_2 avoidance via CCS as 60 %, after taking into account the 15 % increase in the plants total CO_2 emissions from the additional energy usage. The emission intensity of steel production could hence be as low as 800 kg_{CO_2} $t_{HRC}{}^{-1}$. In Chapter 3 it was estimated that fossil fuel substitution by biomass can offset up to 40 % of the CO_2 emissions, reducing the emission intensity of steel production to 1.3 t_{CO_2} $t_{HRC}{}^{-1}$. Deployment of CCS on bioenergy systems results in negative emissions, as CO_2 is extracted from the atmosphere and stored underground. However, a mixture of bio-based and fossil-based fuels occurs during bio-CCS deployment across an integrated steel plant. Tracking accurately the CO_2 balance gives 0.5 t_{CO_2} $t_{HRC}{}^{-1}$ of negative emissions, 1.1 t_{CO_2} $t_{HRC}{}^{-1}$ of avoided emissions, 0.3 t_{CO_2} $t_{HRC}{}^{-1}$ of carbon neutral emissions and 0.5 t_{CO_2} $t_{HRC}{}^{-1}$ of fossil-based emissions, resulting in a net-zero CO_2 balance. Therefore, bio-CCS presents a unique opportunity to achieve carbon neutrality for iron and steel production without relying on successful deployment of technologies in pilot-scale, whist preserving the technical conditions of the current plants close to what they are now.

Even though bio-CCS in iron and steel presents a unique opportunity to reach carbon neutrality via existing technologies, research on bio-CCS for this industry has not been widely discussed. Chapter 3 shows the existence of detailed literature focusing on biomass deployment across the integrated steel plants. A comprehensive document also exists specifically on the CCS deployment for the iron and steel [106]. However, as far as the present author is aware, bio-CCS opportunities have not yet been discussed in depth for this sector, unlike for, e.g., the power sector [3, 200]. This presents an opportunity to study the feasibility of co-deployment of the two technologies together across the European iron and steel plants and reveal whether biomass – in the form of bio-CCS – should be listed as one of the key technologies for achieving the European long-term emission reduction targets.

4.2 BeWhere EU – bio-CCS

In Chapter 3, the iron and steel module was developed within the existing *BeWhere Europe* model to study the availability of biomass resources for such purpose. This chapter follows on this work by developing a CCS module for the *BeWhere EU – iron & steel* model, which allows to compare bio-CCS opportunities across the EU integrated steel plants and study their feasibility for becoming carbon-neutral. The module has incorporated wide range of aspects of CCS, such as CO_2 capture, transport and storage. Details of each as well as the key equations used within the CCS module are presented in this section.

4.2.1 Estimation of CO_2 capture cost

The IEAGHG report "Iron and Steel CCS Study" [106] provides a detailed cost estimate of CO_2 post-combustion capture technology deployment. Following this report, two levels of CO_2 capture rates via standard monoethanolamine (MEA) solvent are also considered in this work. The two levels are labelled here as case 1 and 2, where:

- Case 1 considers capture of CO_2 from flue gases generated at hot stoves and steam generation plant; and
- Case 2 considers capture of CO_2 from flue gases generated at hot stoves, steam generation plant as well as coke ovens underfired heaters and lime kilns.

Their deployment across an integrated steel plant is illustrated in Figure 4.2.

Calculation of the specific CO_2 avoidance cost in this work follows the same methodology and assumptions as within the IEAGHG report [106]. The most substantial assumption to highlight is related to the specific energy use across the iron and steel plant when CO_2 capture is deployed. In detail, it is a common practice that the electricity required

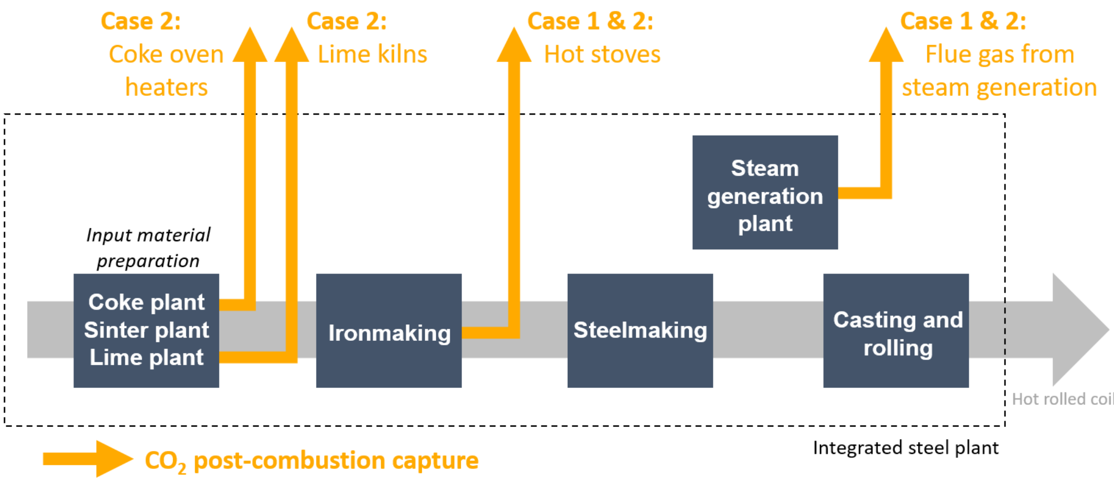


Figure 4.2: CO_2 post-combustion capture opportunities across an integrated steel plant and the distinction between the capture levels.

for the operation of the iron and steel plant is generated on-site from flue gases produced during the iron and steelmaking process. However, the CO_2 capture requires additional energy, which increases the overall energy consumption by the plant. The IEAGHG report assumes that in the case of deployment of the CO_2 capture, the flue gases would be used entirely within the steam generation plant instead, to produce the extra steam demanded by the CO_2 capture plant. The required electricity demand by the iron and steel plant would be met by externally supplying natural gas to the on-site power station. Unfortunately, such assumption would not be viable to apply for this study as some of the integrated steel plants are not connected to natural gas network (e.g., plants in Sweden). Hence this work rather assumes, that in the case of deployment of CO_2 capture technology, all integrated steel plants will be importing electricity directly. Such assumption allows to present differences in the CO_2 avoidance cost for each individual plant, which so far has been presented by the IEAGHG report [106] just as single figure of 73.64 USD $t_{CO_2}^{-1}$ (64.75 € $t_{CO_2}^{-1}$) and 81.15 USD $t_{CO_2}^{-1}$ (71.35 € $t_{CO_2}^{-1}$) for case 1 and 2, respectively.

Obtaining country-specific capture cost from values given at the IEAGHG report [106] requires undertaking seven consecutive steps. First four, summarised in Table 4.1, are to obtain steel production cost without electricity for each CO_2 case:

- Step 1: identify the amount of CO_2 emissions avoided based on the CO_2 emission breakdown provided in Table 4.2;
- Step 2: estimate the steel production cost in USD in 2010, excluding cost of electricity;

Table 4.1: Proceeded steps to obtain cost estimates of steel production with deployed CO_2 capture technology. Calculation based on values provided in the IEAGHG report [106].

Step 1: CO_2 emissions	**Reference**	**Case 1**	**Case 2**
Direct CO_2 emissions (kg ${t_{HRC}}^{-1}$)	2090.14	1041.73	827.42
CO_2 emissions avoided (kg ${t_{HRC}}^{-1}$)		1048.41	1262.72
Step 2: Steel production cost in USD (2010)	**Reference**	**Case 1**	**Case 2**
Steel production cost (USD ${t_{HRC}}^{-1}$)	575.23	652.44	677.7
Electricity consumption (kWh ${t_{HRC}}^{-1}$)	400.1	572.6	621.7
Electricity price (USD MWh^{-1})	143	95	95
Electricity cost (USD ${t_{HRC}}^{-1}$)	57.21	54.4	59.06
Steel production cost without electricity (USD ${t_{HRC}}^{-1}$):	518.02	598.04	618.64
Step 3: Steel production cost in € (2010)	**Reference**	**Case 1**	**Case 2**
Steel production cost (€ ${t_{HRC}}^{-1}$)	429.28	486.9	505.75
Electricity price (€ MWh^{-1})	106.72	70.9	70.9
Electricity cost (€ ${t_{HRC}}^{-1}$)	42.70	40.59	44.08
Steel production cost without electricity (€ ${t_{HRC}}^{-1}$):	386.58	446.3	461.67
Step 4: Steel production cost in € (2017)	**Reference**	**Case 1**	**Case 2**
Steel production cost (€ ${t_{HRC}}^{-1}$)	476.84	540.84	561.78
Electricity price (€ MWh^{-1})	118.54	78.75	78.75
Electricity cost (€ ${t_{HRC}}^{-1}$)	47.43	45.09	48.96
Steel production cost without electricity (€ ${t_{HRC}}^{-1}$):	429.41	495.75	512.82

- Step 3: convert the obtained cost from step 2 to € in 2010, using conversion factor of 1€ = 1.34 USD, as stated within the IEAGHG report [106];

- Step 4: obtain the steel production cost without electricity in € in 2017 by scaling the value obtained in step 3 by factor 1.108 – the inflation factor defined from 01/01/2010 to 31/12/2017 [79].

Production of one tonne of hot rolled coil with deployed CO_2 capture facilities would require 572.6 kWh and 621.7 kWh of electricity for case 1 and 2, respectively, as Table 4.1 shows. Using those electricity consumption estimates and country specific electricity prices for industries with consumption above 70 GWh in 2017 (taking the year average) [61], country-specific CO_2 avoidance cost is calculated by proceeding three more steps:

- Step 5: Obtain electricity cost for production of one tonne of hot rolled coil;

- Step 6: Calculate total steel production cost of one tonne of hot rolled coil;

- Step 7: Find CO_2 avoidance cost by subtracting the reference value of steel production cost in 2017 from the values obtained in Step 6 and dividing it by the given amount of CO_2 avoided for each case.

The intermediate values for steps 5 to 7 are given in Table 4.3. The average CO_2 avoidance cost within the EU is estimated to 64.51 € $t_{CO_2}^{-1}$ and 70.39 € $t_{CO_2}^{-1}$ for case 1 and 2 respectively.

Table 4.2: CO_2 emission split of capture technologies defined in the IEAGHG report entitled "Iron and Steel CCS Study" [106].

a	**Total CO_2 emissions** (kg_{CO_2} t_{HRC}^{-1})	**Captured emissions** (kg_{CO_2} t_{HRC}^{-1})	**Direct CO_2 emissions** (kg_{CO_2} t_{HRC}^{-1})	**% CO_2 avoided** γ_a	**Produced-offset factor** o_a
Reference	2090.14	-	2090.14	-	-
Case 1	2284.86	1243.13	1041.73	50.2	1.18
Case 2	2360.24	1532.82	827.42	60.4	1.21

4.2.2 CO_2 pipeline network development

Currently, no definite CO_2 transport network across Europe is proposed. Therefore, to estimate the expected CO_2 transport cost for each integrated steel plant, this work designed an alternative CO_2 pipeline network that connects each plant to an off-shore CO_2 storage location. As it is highly improbable that all plants would join the most effective CO_2 network, two scenarios are considered to provide a cost range rather than a specific number. The two scenarios are named individual and collaborative. In the individual approach, a direct CO_2 pipeline connects each plant with an off-shore CO_2 storage location closest to it. In the collaborative case, two or more plants could share the pipeline to the storage site. To account for various issues related to pipeline construction, the straight line distance (obtained using the ArcGIS software) is increased by extra 20 % for on-shore pipelines and 10 % for off-shore pipelines. All distances are expressed in kilometres. The connections between the plants in the collaborative network are identified using an established minimum spanning tree algorithm, previously defined also in GAMS [80]. Figure 4.3 presents the proposed CO_2 pipeline network for both cases.

Calculation of the specific CO_2 transport cost for each plant is obtained following a procedure defined previously by an IEAGHG report [105]. The report lists five key steps, which require calculation of:

- CO_2 pipeline diameters;
- Pipeline investment costs;
- Power use and costs for booster stations (using 2017 electricity prices values provided by Eurostat [61]);
- Annual CO_2 transport costs;
- Specific transport costs in € $t_{CO_2}^{-1}$ for each plant.

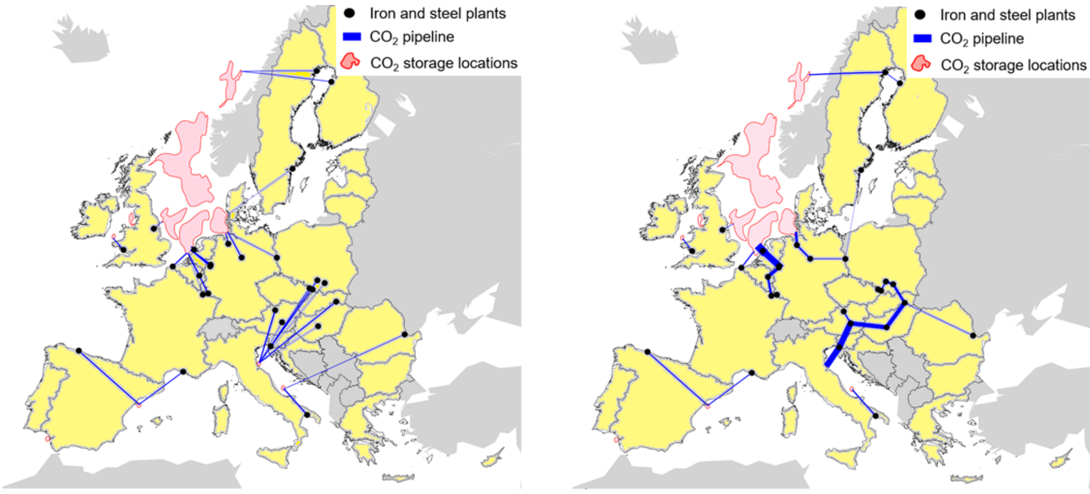
Table 4.3: Estimates of CO_2 avoidance cost using CCS for integrated steel plants across different countries.

Country	Electricity price (€ kWh^{-1}) [61]	**Step 5:** Electricity cost (€ t_{HRC}^{-1}) Case 1	Case 2	**Step 6:** Steel production cost (€ t_{HRC}^{-1}) Case 1	Case 2	**Step 7:** CO_2 avoidance cost* (€ $t_{CO_2}^{-1}$ avoided) Case 1	Case 2
Austria	0.0792	45.35	49.24	541.10	562.06	61.29	67.49
Belgium	0.0718	41.08	44.61	536.83	557.43	57.22	63.82
Czech Republic	0.0782	44.78	48.62	540.53	561.44	60.75	67.00
Finland	0.0633	36.25	39.35	532.00	552.18	52.61	59.66
France	0.0614	35.16	38.17	530.91	551.00	51.57	58.73
Germany	0.1369	78.36	85.08	574.11	597.90	92.78	95.88
Hungary	0.0907	51.91	56.36	547.66	569.18	67.55	73.13
Italy	0.0943	53.97	58.60	549.72	571.42	69.51	74.90
Netherlands	0.0639	36.59	39.73	532.34	552.55	52.94	59.96
Poland	0.0758	43.37	47.09	539.13	559.92	59.41	65.79
Romania	0.0751	43.00	46.69	538.75	559.51	59.05	65.47
Slovakia	0.1108	63.44	68.88	559.19	581.71	78.55	83.05
Spain	0.0870	49.82	54.09	545.57	566.91	65.55	71.33
Sweden	0.0501	28.66	31.12	524.41	543.94	45.37	53.14
United Kingdom	0.1381	79.05	85.83	574.80	598.65	93.44	96.47
Average	0.0851	48.72	52.90	544.47	565.72	64.51	70.39

* Values used as $p_{r,a}^{CO2capture}$ parameter defined in Section 4.2.4

In the case of the collaborative network, CO_2 transport cost for each plant is considered from the point where the CO_2 is produced until reaching the CO_2 storage. The contribution of each plant towards the pipelines' cost is proportional to its share of the CO_2 volume flowing through the evaluated segment. By plants sharing some of the costs of the pipeline network, the net cost of transporting one tonne of CO_2 decreases for most of them. The decrease in the CO_2 transport cost is despite the fact that their CO_2 generally travels in total a longer distance than in the case of the individual approach.

As the estimation of CO_2 transport cost is based on work performed in 2005 [105], the final values are scaled by an inflation factor of 1.20 to provide values corresponding the costs in 2017 [167]. The final estimates are given in Table 4.4. It is important to note that the analysis of CO_2 transport cost assumes a concurrent development of the whole CO_2 pipeline network, i.e., all plants start to transport CO_2 on the same day. This means all pipelines are straight away designed based on plateau flow, which is in practice close to impossibility. In reality, the pipeline network is built gradually, which would raise additional costs due to unused capacity - an aspect not considered within this analysis.



(a) Individual approach (b) Collaboration approach

Figure 4.3: Proposed CO_2 pipeline network that connects each integrated steel plant with an off-shore CO_2 storage.

4.2.3 CO_2 storage

This work considers only off-shore CO_2 storage in either saline aquifers or depleted oil and gas fields. On-shore CO_2 storage is not considered due to the current development in the public opposition on this topic across Europe. The estimates of the off-shore CO_2 storage capacities and locations are taken from the Chalmers CO_2 storage database [119]. The costs of actual CO_2 storage are taken from the ZEP report [255] and scaled by an inflation factor of 1.09 to obtain 2017 estimate values of 10.80 € $t_{CO_2}^{-1}$ for depleted oil and gas fields and 15.60 € $t_{CO_2}^{-1}$ for saline aquifers [167].

4.2.4 CCS module

Cost of the CCS deployment, and the corresponding CO_2 emission reduction achieved, are introduced into the *BeWhere EU – iron & steel* model using the CCS module. The module interaction with the rest of the model is shown in Figure 4.4.

The amount of CO_2 emissions avoided $e_{r,p}^{CCS}$ is obtained for each plant using CO_2 avoidance efficiency of each technology γ_a and current emission intensity of each plant $\bar{e}_{r,p}^{present}$. In addition, binary variable $k_{p,a}$ is used to control whether CO_2 capture technology a is

Table 4.4: CO_2 transport cost for each plant under individual and collaboration scenario. The listed values are used for parameter $p_{r,p}^{CO2Transport}$ defined in details in Section 4.2.4.

Plant i	**Individual approach** € $t_{CO_2}^{-1}$	**Collaborative approach** € $t_{CO_2}^{-1}$
AUT1	6.77	4.47
AUT2	14.71	3.19
BEL	2.56	2.86
CZE1	12.92	11.41
CZE2	16.78	10.95
DEU1	5.83	4.81
DEU2	2.43	1.72
DEU3	3.09	1.88
DEU4	3.12	2.31
DEU5	1.49	0.92
DEU6	4.94	4.88
DEU7	23.38	1.81
DEU8	9.99	6.07
ESP	8.19	8.19
FIN	18.16	14.39
FRA1	4.72	4.66
FRA2	10.05	10.05
FRA3	11.52	4.31
GBP1	2.41	2.41
GBP2	3.35	3.35
HUN	22.56	5.60
ITA1	3.92	3.92
ITA2	36.66	1.52
NLD	0.52	0.19
POL1	28.45	9.34
POL2	12.61	9.96
ROU	21.93	17.71
SVK	11.23	7.73
SWE1	14.33	8.46
SWE2	24.44	63.25
Average	11.44	7.74

deployed. Variable $e_{r,p}^{CCS}$ is hence defined as:

$$e_{r,p}^{CCS} = \sum_{a=1}^{2} \gamma_a \times k_{p,a} \times \bar{e}_{r,p}^{present}, \qquad \forall \quad r \in \tilde{R}, \quad p \in \tilde{P}. \tag{4.1}$$

Additional expenditure related to the deployment of CCS technology consists of CO_2 capture, transport and storage costs (represented as variables $c_r^{CO2capture}$, $c_r^{CO2Transport}$ and $c_r^{CO2Storage}$), defined in Equations 4.2 on the next page. Each cost depends on the corresponding parameter ($p_{r,a}^{CO2capture}$, $p_{r,p}^{CO2Transport}$, and $p_{r,p}^{CO2Storage}$), which defines the price per tonne of CO_2 avoided. It is important to note that the parameter defining the price of CO_2 capture $p_{r,a}^{CO2capture}$ is specific for the region r and the CO_2 capture case a (either case 1 or 2 which differences are shown in Section 4.2.1) deployed. Parameters defining price of CO_2 transport and storage, $p_{r,p}^{CO2Transport}$ and $p_{r,p}^{CO2Storage}$, are specific for the plant p and the corresponding region r the plant is in. The cost of transport and storage of the extra CO_2 generated due to the additional energy demand (resulting from the deployment of CO_2 capture) is included in the equations using parameter o_a. The values considered for parameter o_a, for each capture case a, are presented in Table 4.2.

$$c_r^{CO2capture} = \sum_{p=1}^{P}\sum_{a=1}^{2} p_{r,a}^{CO2capture} \times \gamma_{p,a} \times k_a \times \bar{e}_{r,p}^{present} \tag{4.2a}$$

$$c_r^{CO2Transport} = \sum_{p=1}^{P}\sum_{a=1}^{2} p_{r,p}^{CO2Transport} \times \gamma_{p,a} \times k_a \times \bar{e}_{r,p}^{present} \times o_a \tag{4.2b}$$

$$c_r^{CO2Storage} = \sum_{p=1}^{P}\sum_{a=1}^{2} p_{r,p}^{CO2Storage} \times \gamma_{p,a} \times k_a \times \bar{e}_{r,p}^{present} \times o_a \tag{4.2c}$$

$$\forall \quad r \in \tilde{R}$$

The CCS module is based solely on one constraint, which ensures only one CO_2 capture case (either case 1 or 2) is selected. This constrain is defined as:

$$\sum_{a=1}^{2} k_{p,a} \leq 1, \qquad \forall \quad p \in \tilde{P}. \tag{4.3}$$

As the deployment of the CCS technology impacts the total cost c_r as well as the total emissions e_r of the system, their modifications are required. In detail, the previously defined Equation 3.7 now becomes

$$\begin{aligned} c_r = & c_r^{BiomassDomestic} + c_r^{BiomassImported} + c_r^{BiomassNonEU} \\ & + c_r^{BiomassTransport} + c_r^{BioProduction} + c_r^{FossilSteel} \\ & + c_r^{CO2capture} + c_r^{CO2Transport} \\ & + c_r^{CO2Storage}, \qquad \forall \quad r \in \tilde{R}, \end{aligned} \tag{4.4}$$

expanded by the variables representing the cost of CO_2 capture, transport and storage. Similarly, Equation 3.8 now changes to:

$$e_r = e_r^{FossilSteel} - \sum_{p=1}^{P} e_{r,p}^{CCS}, \qquad \forall \quad r \in \tilde{R}, \tag{4.5}$$

subtracting the amount of CO_2 avoided due to the deployment of CCS.

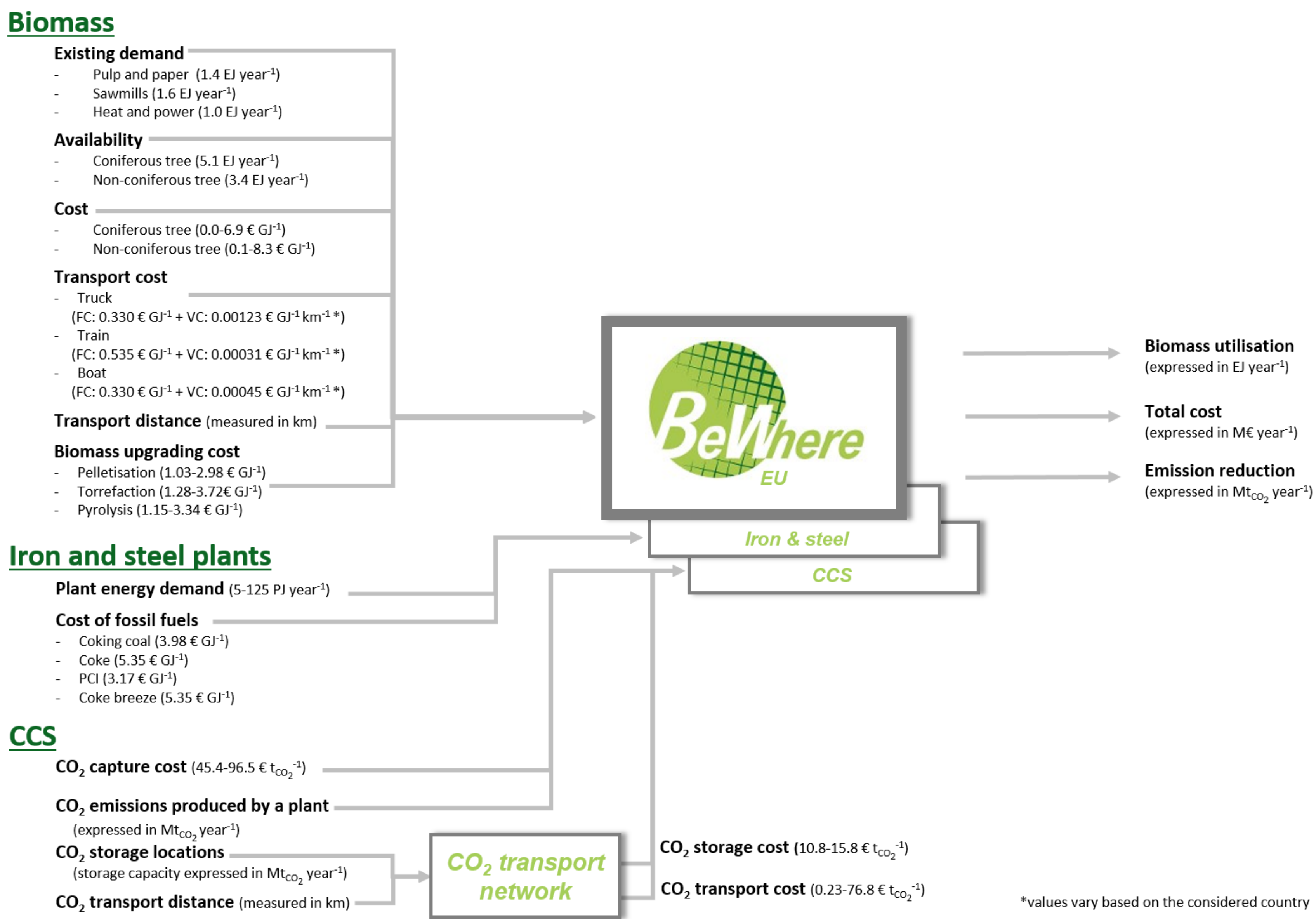


Figure 4.4: Structure of the *BeWhere EU – iron & steel* model to study bio-CCS opportunities.

4.3 Results and discussion

4.3.1 Roadmap towards carbon neutrality via bio-CCS deployment

Bio-CCS deployment and its CO_2 avoidance cost

Chapter 3 previously identified differences in biomass supply cost across the countries as well as individual integrated steel plants and similar trend is observed here for the bio-CCS. Figure 4.5 demonstrates the most economical way to achieve specific CO_2 reduction targets for the EU iron and steel industry via the deployment of either biomass, CCS or bio-CCS. First thing to note is that CCS is never identified as an optimum technology on its own. Each plant starts with biomass deployment, followed by co-deployment of CCS. For most of the cases though, the co-deployment of CCS starts before reaching the full technically-feasible biomass use. Mere partial fossil fuel switching is sufficient for targets aiming to achieve up to 20 % of CO_2 emission reduction. This would be reached by each plant applying a certain level of biomass, which in real life might be highly improbable due to technical, economical and practical reasons as well as preferences by the plant operators in other low carbon technologies. On the other hand, the findings show that bioenergy is a key technology to achieve particularly the initial decarbonisation of the industry.

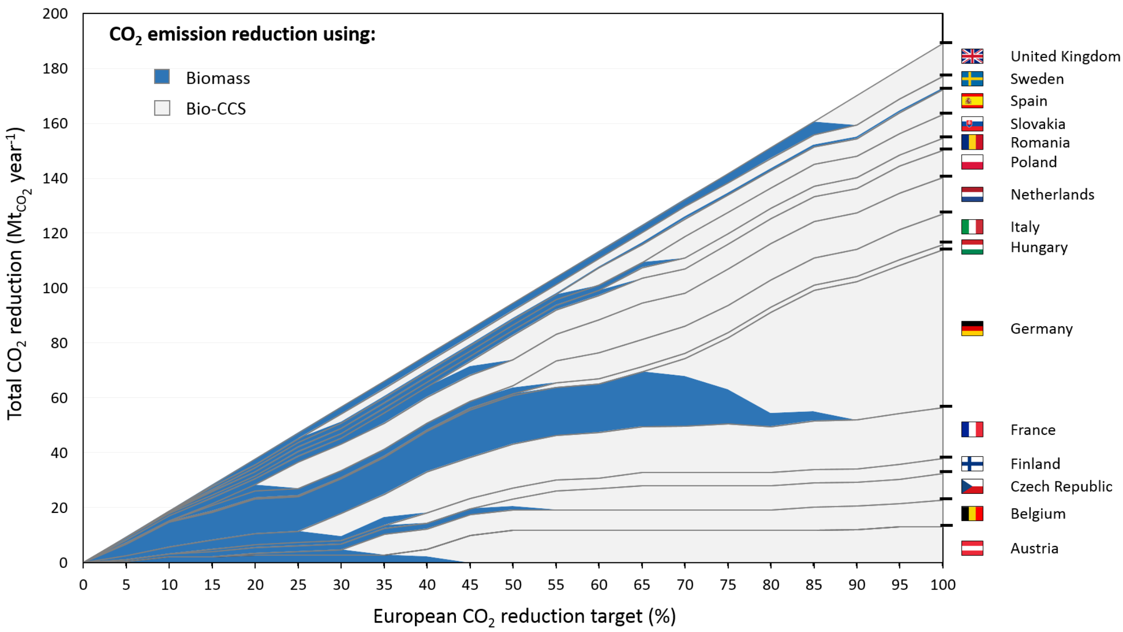


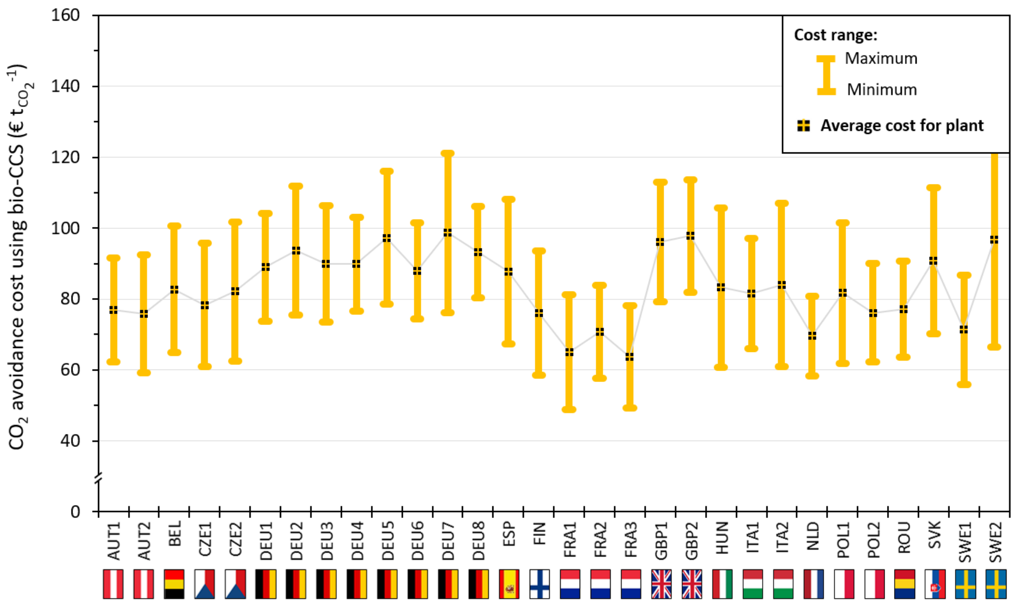
Figure 4.5: Technology roadmap towards carbon-neutral iron and steelmaking in Europe.

Figure 4.5 also shows that the share of emission reduction for each target is almost proportional to the amount that each country contributes. This is an important observation as it demonstrates that all countries should deploy efforts to decarbonise their integrated steel plants. In other words, the targets would not be achieved by decarbonising a certain plant or plants within a certain country, but rather joint-efforts are necessary. For example, one might suggest to push for carbon neutrality across the German integrated steel plants, as that on its own could already achieve European CO_2 reduction target of 30 %. But as Figure 4.5 shows, Germany is one the leading countries for biomass deployment but not for CCS. Bio-CCS in Germany becomes preferential when aiming to achieving European CO_2 reduction targets of 60 % and higher.

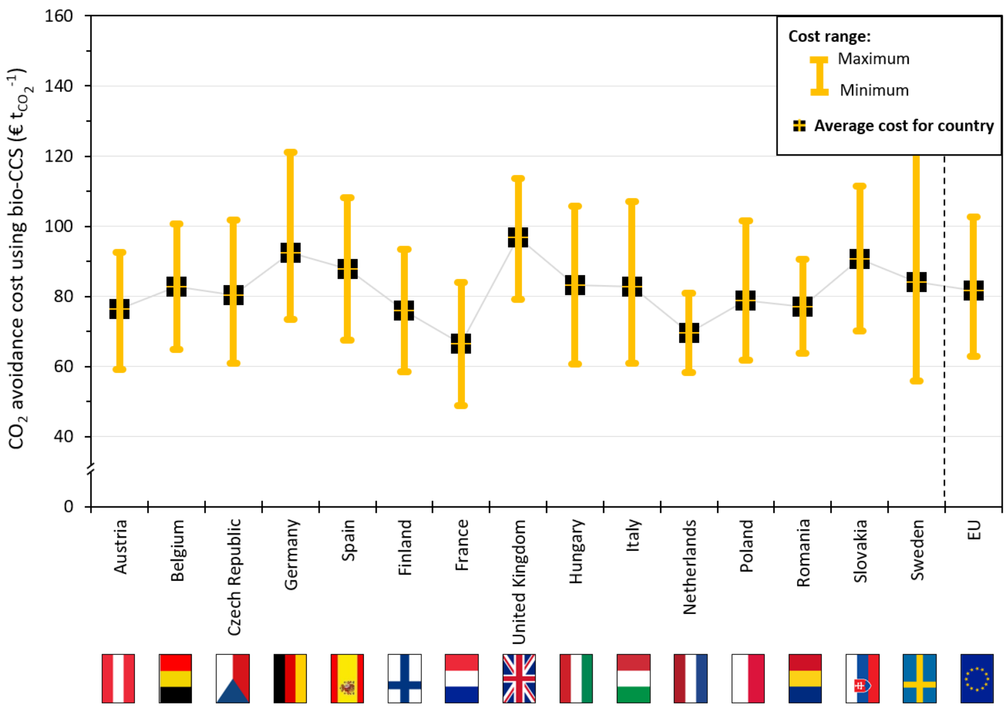
As CO_2 reduction targets across Europe become stronger, the first deployment of bio-CCS would be expected in Netherlands, followed by the three plants in France and a plant in Sweden (SWE1). These countries/plants also have the lowest average CO_2 avoidance cost using bio-CCS as shown in Figure 4.6. In detail, the plant in Netherlands of 70 € ${t_{CO_2}}^{-1}$, French plants between 64 and 71 € ${t_{CO_2}}^{-1}$ and a Swedish plant (SWE1) of 71 € ${t_{CO_2}}^{-1}$ as well. Reasons for their low bio-CCS avoidance costs include the ability to source sufficient amount of biomass, cheap electricity for industrial applications and close location of the plants to the CO_2 sinks in the North Sea. Another country for which one can expect relatively early deployment of CCS is Belgium. This might be particularly due to its high reliance on imported biomass, as shown in the Chapter 3, and its close location to the North Sea. However, reaching full carbon neutrality of the plant would be of an average cost of 83 € ${t_{CO_2}}^{-1}$ avoided.

Relatively delayed CCS deployment, after high level of biomass use, is observed for Germany, the UK and a plant in Sweden (SWE2). Figure 4.6 shows that those are the countries/plants, which have one of the highest CO_2 avoidance cost using bio-CCS. Specifically, Germany and UK present comparably high average CO_2 avoidance cost of 92 and 97 € ${t_{CO_2}}^{-1}$, respectively. It is important to note that those countries have relatively high electricity prices for industry [61], which impact on the bio-CCS cost is discussed later. On the other hand, high CO_2 avoidance cost of the Swedish plant SWE2 of 97 € ${t_{CO_2}}^{-1}$ (which could reach up to 127 € ${t_{CO_2}}^{-1}$) is largely due to its CO_2 transport cost. In detail, this work proposed joining SWE2 plant with the German CO_2 pipeline network (Figure 4.3(b)), rather than defining a route that would go directly to the CO_2 sink location. Collaborative network for the SWE2 plant is not economically beneficial, and CO_2 transport via ships or more direct pipeline network might be preferential for this plant in reality.

In general, achieving carbon-neutrality across the EU integrated steel plants would be of CO_2 avoidance cost of 82 € ${t_{CO_2}}^{-1}$. However, this is only an average. Range of biomass



(a) CO_2 avoidance cost - plant level



(b) CO_2 avoidance cost - country level

Figure 4.6: Range of CO_2 avoidance cost using bio-CCS on plant and country level.

supply costs, technology specifications and sharing CO_2 pipelines between plants can offset certain amount of CO_2 from as little as 62 € $t_{CO_2}^{-1}$ and as much as 102 € $t_{CO_2}^{-1}$. Hence carbon price has to be at least 60 € $t_{CO_2}^{-1}$ for the European integrated steel plants to seriously start considering bio-CCS. Achieving carbon-neutrality would require imposing carbon price of a minimum of 80 € $t_{CO_2}^{-1}$.

Impact of bio-products, CO_2 capture, transport and storage on the final CO_2 avoidance cost

CO_2 capture is taking the biggest share in the CO_2 avoidance cost using bio-CCS, followed by the additional expenditure from the use of bio-products. Figure 4.7 presents a pie chart showing the contribution of bio-products as well as CO_2 capture, transport and storage to the final bio-CCS avoidance cost in percentage. On average, CO_2 capture takes about 50 % of the CO_2 avoidance cost. As a result, the CO_2 capture cost influences the economic viability of bio-CCS the most. This explains why the plants with the highest CO_2 avoidance cost in Figure 4.6 also have the greatest share of CO_2 capture cost in their cost evaluation in Figure 4.7. Plants with particularly high CO_2 capture cost are located in Germany and the UK, accounting for 60% of the total CO_2 avoidance cost using bio-CCS. It is important to note that the cost of a first-of-a-kind capture plant would be significantly greater than the cost of a mature nth-of-a-kind [189]. Therefore, it is highly probable that the capture cost will decrease as technology learning starts. The CO_2 capture cost might then be also less impacted by the energy costs within the given countries and increase the economic viability of CCS/bio-CCS deployment across the UK and German plants.

Bio-products take the second biggest share in the CO_2 avoidance cost when reaching carbon-neutrality via bio-CCS. Bio-products contribute to about 30 %, however, plants heavily reliant on imported biomass, such as the Netherlands and Belgium, have this share over 40 %. The lowest contribution of bio-products to CO_2 avoidance cost is for a plant in Italy (ITA2) and Romania. For those biomass accounts for only 20 % of the additional cost. Unlike as for the case of CO_2 capture discussed in the previous paragraph, increase in deployment of bio-products across iron and steel plants could actually raise their cost and the corresponding share in the CO_2 avoidance cost. For example, work by Olofsson [168] concludes that the deployment of bio-products within a Swedish integrated steel plants would increase the overall cost of biomass for other applications due to the resulting competition for biomass resources.

Large differences between plants could be observed particularly for the CO_2 transport costs. As can be observed from Figure 4.7 again, the contribution of CO_2 transport to

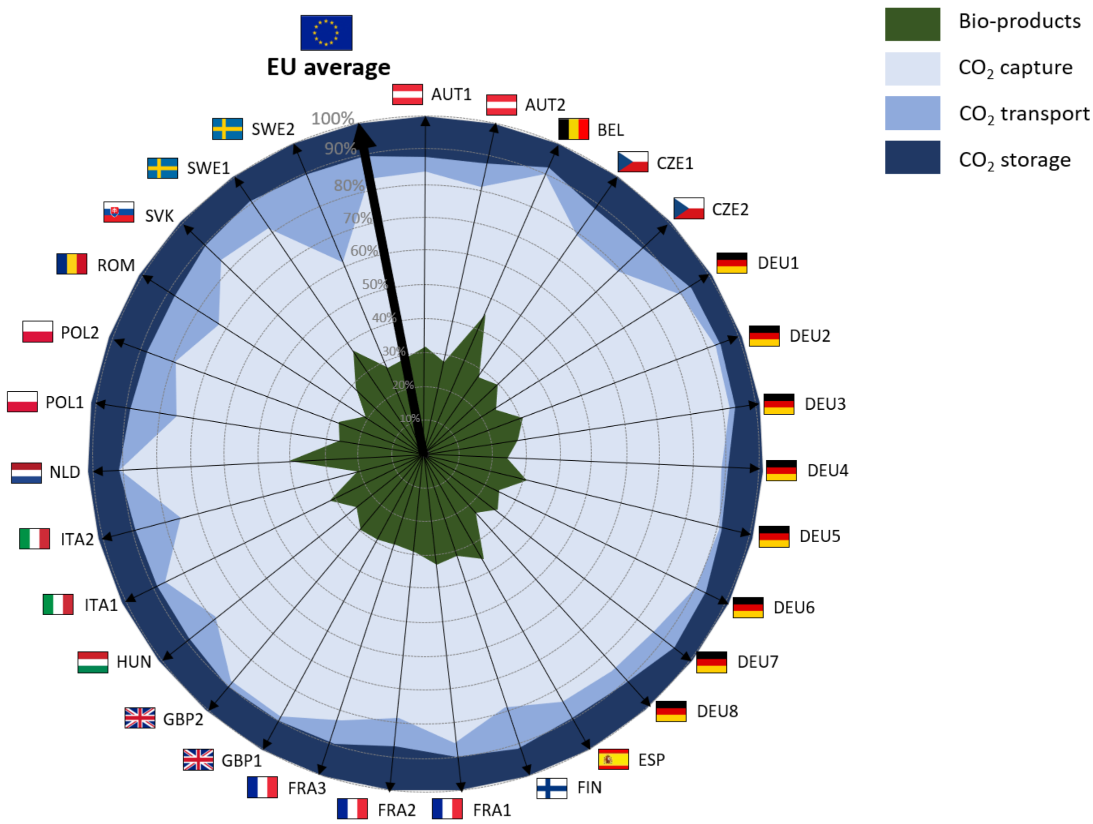


Figure 4.7: Contribution of bio-products, CO_2 capture, CO_2 transport and CO_2 storage cost to the final CO_2 avoidance cost using bio-CCS, when bio-CCS is deployed in the maximum capacity to achieve carbon-neutrality across Europe. Differences shown on plant level.

the CO_2 avoidance cost could be almost negligible (e.g., NLD plant) or have a significant share (e.g., SWE2 plant). It is important to note that the CO_2 transport estimates are derived from a proposed network demonstrated in Figure 4.3. However, building such network would face a lot of economic as well as technical, legislatorial and social barriers. The next section discusses those, as they could completely preclude any bio-CCS/CCS deployment in the future.

4.3.2 Non-economic barriers limiting CCS deployment

So far, this work focussed only on economic barriers when studying the opportunities for bio-CCS integration across the European iron and steel plants. But, as mentioned before, social and technical factors are equally important when considering feasibility of any bio-CCS system. To provide a better understanding of the bio-CCS prospect in Europe, an additional overview of the non-economic barriers that are specifically limiting

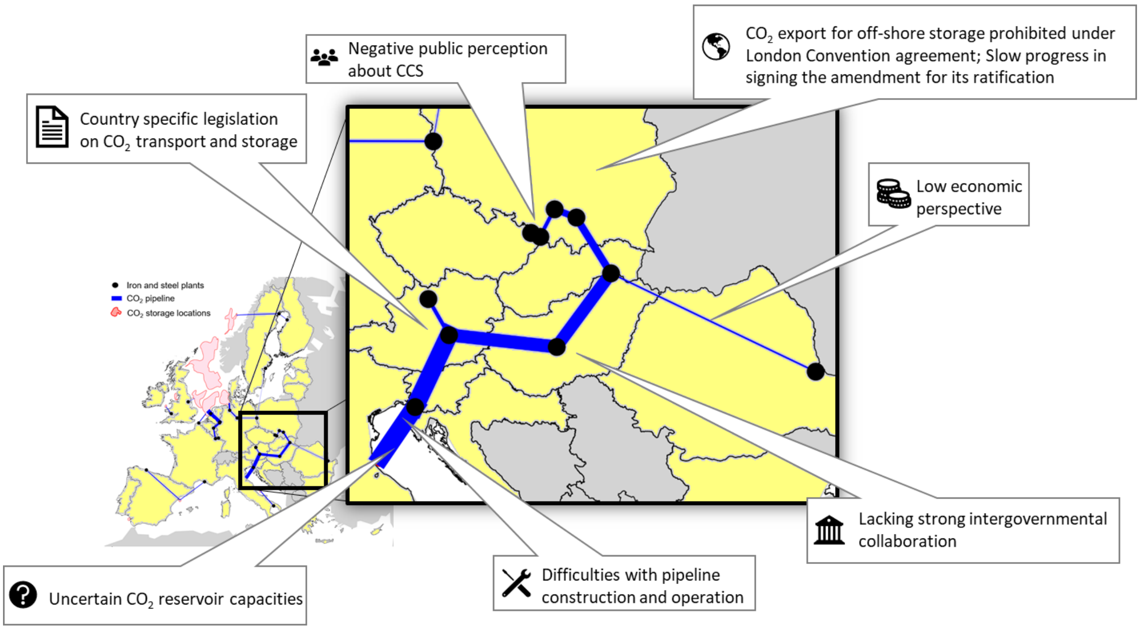


Figure 4.8: List of barriers limiting current CCS implementation in Europe. Specific example is provided for the proposed pipeline in this work located across Eastern and Central Europe.

the implementation of CCS is provided in this section. Central and South-East European pipeline network leading to the offshore saline aquifer "Emilia mare" in the Adriatic Sea is used here as an example (accompanied by Figure 4.8), however, the listed barriers are in various forms across the whole Europe.

One barrier that may suspend or even completely discard deployment of CCS is public opposition, as demonstrated by for instance the Barendrecht project in the Netherlands [121]. It is possible that the large pipeline network of over 2,000 km shown in Figure 4.8 may face considerable public opposition, as it runs through highly populated urban centres (see for instance the large oil pipeline network in North Dakota in 2016 [187]). Ship transport could possibly be one solution. However, it is doubtful whether this is technically and practically feasible with the large CO_2 volumes that need to be treated (intermediate storage, liquefaction) and transported. Hence the EU should work on increasing public awareness of CCS/bio-CCS and its acceptance among the general public, before it is defined as a key strategy for the industry.

Legislation and international agreements currently taking place also need modification to be able to build such network. The EU has a CCS Directive [50] already in place, which establishes a legal framework for the CO_2 storage. However, Poland, Hungary and Italy (as well as other countries with iron and steel industry outside this focused network, such as Sweden, UK, Spain, France, Belgium, Netherlands, Germany) are also Parties to the London Convention and Protocol [109]. This international treaty, where Article 6 prohibits export of waste and other matter for disposal at other country's sea, prohibits transboundary transport of CO_2 for geological storage. Ratification of an amendment to the protocol from 2009, which allows export of CO_2 for storage, requires signature of two thirds of the members of the protocol. The signing of the amendment has turned out to be a very slow process, as only five out of the required twenty-nine countries have signed by mid-2018, which makes its ratification unrealistic in the near future. However, discussions are on-going whether bilateral agreements between the exporting and importing country may be sufficient under the amendment [96]. One of the options to bypass the London Protocol is to use the captured CO_2 for enhanced oil recovery (CO_2-EOR). The limited possibilities for CO_2-EOR in the Europe, particularly in the area of the Adriatic Sea, do not make this leverage possible unfortunately. The temporal forbiddance of on-shore CO_2 storage for countries in Figure 4.8: Austria, Czech Republic and Poland [190] makes networks for off-shore storage still the most preferential option.

Finally, most estimates of CO_2 storage capacity in aquifers are usually very uncertain [119]. In order to know the storage and injection capacity in any aquifer, drilling and actual injection of CO_2 would be necessary, which is particularly expensive off-shore. Contracts between companies capturing CO_2 and CO_2 storage providers committing to supply certain amount of CO_2 (defined annually or over a certain time-frame), are likely to be necessary. Those would then motivate the storage providers to perform the costly off-shore drilling, after very thorough on-land investigations. Provided a storage site with sufficient storage capacity is identified, a final investment decision can then be taken on the capture plant. This illustrates some potential barriers for the CO_2 storage part in the CCS chain, and without an economic reward, there is no motivation for the industry to carry out the huge investments required for a CCS scheme. To help to overcome this problem, one possible solution is that the identification and certification of the first storage sites is financed by the government, at least partly. The North Sea is one possible exception in Europe due to the extensive knowledge of the subsurface and Equinors (former Statoil) committed interest in making CCS a business case.

The "Emilia mare" aquifer studied in detail here, has limited effective storage capacity (considering technical cut-off limits) [8]. In other words, it might not be enough to store the CO_2 transported in the pipeline shown in Figure 4.8. Besides, Italy may require the available storage capacity for own purposes. Hence, the pipeline network illustrated in Figure 4.8 may be re-routed to storage in the North Sea instead [154, 158], despite the fact that this will require a much longer and more expensive pipeline network. More specifically, the estimated CO_2 storage capacity in "Emilia Mare" ranging from 657 to 2628 Mt_{CO_2} [41] can fill up the site in less than 20 years assuming an annual storage requirement of 35.3 Mt_{CO_2}. This will limit any additional plants to join the CO_2 network throughout the time. In addition, other Italian industries may be interested in using the CO_2 storage sites in Italian waters, and thus Italy may not be willing to import CO_2 for storage, and rather utilise their scarce resource for themselves in the future. Other potential CO_2 storage reservoirs in the Adriatic Sea, such as Abruzzi Mare, can enhance the CO_2 storage capacity potential. Uncertainty in the storage capacities contributes to the overall unpredictability of the CCS infrastructure for European iron and steel, which needs to be overcome first before the industries will ever commit to CCS/bio-CCS.

4.3.3 Bio-CCS vs. other options for achieving carbon neutrality

The most promising technologies that could achieve carbon-neutral iron and steel making in Europe currently include direct reduction using hydrogen (as long as the hydrogen is sustainably sourced, which is not the case at the moment) and electrolysis. However, deployment of either of those would require existing plants to divert from the traditional iron and steel making production route via BF-BOF, unlike during the deployment of bio-CCS. Details of each, supported by discussion on their feasibility to become fully commercialised in the near future, are given below.

Direct reduction using hydrogen

Direct reduction process using hydrogen (Hydrogen-DR) has been already introduced in Chapter 1. In terms of energy requirement, Vogl *et al.* [234] calculated that production of one tonne of crude steel would require 3.48 MWh of electricity, mainly for the hydrogen production via electrolysis. This would indeed require an addition of a large electricity generation capacity. For example, a typical plant producing 4 million tonne of crude steel a year would require a 1.59 GW power plant to meet the electricity demand. In terms of economic viability of Hydrogen-DR, Vogl *et al.* [234] state that Hydrogen-DR could become competitive already at carbon prices ranging between 34 to 68 € ${t_{CO_2}}^{-1}$. However, the economics of this route are highly sensitive to the price of electricity used for the hydrogen production. Vogl *et al.* [234] considered electricity cost of 40 € MWh^{-1}, as they were performing the case study for Sweden. But Swedish electricity prices are one of the lowest in the EU, as can be observed from Table 4.3. Hence realistically, the carbon prices that would make Hydrogen-DR competitive would have to be even higher. At the same time, 95 % of global hydrogen production is currently generated from fossil fuels, via steam methane reforming of natural gas, coal gasification or cracking oil products in refineries [177]. To achieve the needed emission savings, the hydrogen would have to be produced by water electrolysis, using electricity generated from sustainable energy sources such as hydropower or biomass power plants. Supplying the required amount of electricity from those sources would be highly challenging for most European countries.

Apart from the economical side, also technical concerns related to Hydrogen-DR exist. First, steel production using hydrogen presents high safety risks, as hydrogen is highly explosive. In addition, the amount of hydrogen that would be required for iron ore reduction is enormous. This raises multiple issues. First one in terms of supply; considering the current global hydrogen production of 60 Mt y^{-1} and the estimated requirement of 75 kg of hydrogen for production of one tonne of crude steel [177], converting just one integrated steel plant of output 4 Mt_{CS} y^{-1} to Hydrogen-DR would currently use 0.5 % of global hydrogen. Second, having sufficient amount of hydrogen available for the iron and steel production would mean developing large hydrogen storage on-site, which adds up to the cost and safety concerns. Third, direct reduced iron (also called sponge iron) produced using hydrogen would have none or very negligible amount of carbon, an important element in the alloy that ensures its proper metallurgical properties, for instance, strength. Therefore, extra carbon would have to be introduced to the process, e.g., at the electric arc furnace (EAF) when producing steel, which is much harder to do. Additional carbon might be also needed for the required slag forming.

Therefore, even though achieving carbon-neutrality via hydrogen is good from the environmental principle, practically it has a long way to go. Hydrogen-DR is relying on development of technologies on-site of the iron and steel plants as well as off-site. It is true that CCS/bio-CCS requires the development of CO_2 infrastructure off-site of a plant too, however, CO_2 transport and storage is currently more economically feasible and practical than creating large-scale hydrogen infrastructure that the plants would need. On the other hand, use of hydrogen would reduce the plants' dependence on resources that are scarce in Europe, like coking coal [54], and make, e.g., Sweden self-sufficient in sourcing all raw materials required for the steel production. Biomass introduction could reduce the reliance of EU on coking coal imports as well, but only by a slight fraction when compared to the opportunities presented by hydrogen.

Electrolysis

Electrolysis, a process during which iron ore is reduced using electricity, could also produce steel from raw materials of zero or close to zero carbon footprint, as mentioned in Chapter 1. The ULCOS programme have focused particularly on the option of aqueous alkaline electrolysis, called electrowinning. Even though the research findings present promising results, the technology is in very early stages [177], unlike say the widely used Hall-Héroult process for aluminium extraction. Also, the targeted environmental benefit would be achieved only if the used electricity comes from renewables, which supply electricity in highly variable intervals. Getting the electrowinning technology to be able to respond to such variation in the electricity supply would be challenging. Even Hydrogen-DR has higher potential to work with variable electricity generation than electrowinning, as hydrogen production can respond better to those fluctuations and keeping the iron ore reduction process consistent. In terms of the overall energy demand though, electrolysis is the most energy- and resource-efficient production route from all [177]. Production of one tonne of crude steel would require around 2.6 MWh of energy. A plant of production output of 4 Mt_{CS} y^{-1} would require a power supply equivalent to power plant of output 1.19 GW. The challenge to be able to provide to one plant such amount of electricity from renewables would be greatly challenging. Comparing electrolysis specifically with the bio-CCS, bio-CCS presents multiple advantages. First, bio-CCS preserves the current processes and plants, which reduces the capital investments. Second, is easily linkable with the existing energy systems and third, it is able to be deployed in the very near future.

4.4 Chapter summary

By developing a CCS module for the *BeWhere EU – iron & steel* model, this chapter studied the feasibility of bio-CCS to achieve carbon-neutral iron and steelmaking in Europe. The results show that the continual decarbonisation should start by introducing bioenergy to all plants first, followed by the co-deployment of CCS on top. In other words, it is never preferential to deploy CCS first on its own. It is expected that Netherlands, France and a plant in Sweden (SWE1) would be the first countries initiating bio-CCS deployment. On the other hand, CCS deployment would be probably delayed for plants in Germany and the UK. Both of the countries show high CO_2 capture cost, which is the most expensive component of bio-CCS technology for all plants. Achieving full carbon neutrality via bio-CCS across the European integrated steel plants would cost on average 80 € $t_{CO_2}^{-1}$ avoided.

Apart from the issues related to the economic viability of bio-CCS, the CCS component, in particular, is facing various technical, regulatory and social barriers. On the other hand, reaching carbon-neutrality via bio-CCS is still more promising that via Hydrogen-DR or electrolysis, as those technologies are still in a development stage. Therefore, bio-CCS should be considered as one of the long-term emission reduction strategies. The roadmap towards achieving a full carbon-neutrality should ideally start with the bioenergy deployment in the near future, in order to also meet the initial targets (below 20 %). Proceeding efforts to build the CO_2 transport infrastructure should be undertaken meanwhile to create groundwork that enables transfer towards bio-energy co-deployment with CCS in the next decades.

Chapter 5

Bioenergy deployment as an economic, environmental and broader strategic decision

Deployment of bioenergy for iron and steelmaking in the EU should be based on assessment that not only evaluates economic viability and emission reduction potential, but also analyses whether this decision supports strategic use of the limited biomass resources worldwide. Hence the present work addresses a third research question:

> *Which EU countries should seriously consider bioenergy deployment within their iron and steel industry, as it would be a strategic energy-use decision?*

By developing the *Global Suitability Index*, the present work studies the suitability of bioenergy deployment for iron and steelmaking in each EU country based on the size of their steel industry, national biomass resources and supportive policies. The obtained findings are also compared to the estimated CO_2 avoidance costs presented in the previous chapters, providing a comprehensive judgement whether or not biomass integration within the European iron and steel industry is a well-founded strategy.

The chapter findings have been previously published in the Journal of Sustainable Energy Technologies and Assessments in Mandova *et al.* [138]. The model development and the content write-up were both performed by the present author, to which co-authors of the joint publication contributed by providing a guidance and expertise.

5.1 Non-economic benefits of local biomass systems

During decision making stages, it is important to compare the economic aspects against the social and environmental benefits or harms that a bioenergy system can create. Unfortunately, those social and environmental gains are often harder to quantify than the economic ones. Dale *et al.* [32] propose six socio-economic indicators by which sustainability of bioenergy systems could be measured. Those include impact of the bioenergy system on the social well-being, existing energy security of the country, current external trade, profitability of the bioenergy system, resource conservation status and social acceptability of such projects. There is often a tendency during evaluation of bioenergy systems to focus on these aspects, but only on one industry or sector in isolation, not recognising the inter-sectoral linkages [224]. A common example is considering only the emission savings at the biomass consumer side, not accounting for the environmental impact of the biomass production.

Measuring different non-economic benefits or harms increases in simplicity and accuracy the more local the bioenergy system is, i.e., the closer the supply region is to the demand region. In addition, deployment of bioenergy systems at the locations containing both, biomass suppliers and consumers, could enhance the local economy, give the biomass consumers a better opportunity to control the sustainable sourcing of the supplied biomass as well as offset emissions that would otherwise result from the long distance bulk transport. The next sections discuss each of those points in further detail.

5.1.1 Enhancement of local economy

Sourcing biomass locally could have a positive socio-economic impact within the region. In detail, utilisation of geographically-convenient biomass resources could increase the energy access, provide regional economic gain and boost employment. Such a new employment and income-generating source would particularly benefit rural areas, which are experiencing outward migration [40]. Work by Thornley *et al.* [216] focusing on biomass power plants calculates that on average 1.27 job years are provided for each GWh of electricity produced from them. The majority of these jobs are even long-term, due to high labour requirement for plant operation and biomass supply. Bioenergy deployment could also positively impact related industries in the area, particularly the ones in farming and renewable energy. For example, the GRAZE Gas project under construction in County Cork in Ireland set to produce renewable natural gas via anaerobic digestion plants will, apart from emission reduction, also increase profitability of the nearby farmers, who will be contracted to supply manure for those plants [15]. In general, bioenergy deployment and the corresponding increase in regional productivity could then enhance the regional attractiveness to inward investment. In the case of excess biomass resources, deployment of a bioenergy system could also generate an export industry. On top, Domac *et al.* [40]

state that successful bioenergy production could increase ecosystem conservation and even rehabilitation.

A bioenergy system could present a new access route to energy supplies. This will be particularly attractive for energy importing regions, for which it would be an opportunity to increase their energy independence [40]. The overall energy dependence of the EU in 2016 was 53.6 %, however, the dependence of some countries exceeds 95 % (e.g., Cyprus, Luxenbourg and Malta) [62]. Being able to utilise domestic resources would contribute towards the efforts to reduce the EU's reliance on energy imports. On top, fossil fuel market is highly fluctuating, and even though biomass prices present volatility too [120], its fluctuation is lower when compared to fossil fuels meaning fuel-switching would reduce the corresponding economic impact. Substitution of fossil fuels by biomass also brings local health benefits, for example by avoiding SO_2 emissions resulting from coal combustion [203]. It is important to note that the extent of all these benefits would vary for each specific location and stages in the overall bioenergy system cycle.

5.1.2 Assurance of sustainable biomass production

Regional sourcing of biomass is also the most powerful way to ensure that the consumed biomass has not induced or enhanced deforestation in the place of the biomass origin. For it to be assumed that biomass has been produced in a sustainable and environmentally friendly manner, an evidence is necessary to prove that it satisfies international criteria set for international biomass trade, for example, via certification, which set standards for different sustainability criteria including the GHG emissions, energy balance or water protection [176]. However, even though these criteria are comprehensive, they still may not address all sustainability aspects. For example, some argue that these criteria are actually much more stringent at some places than what is necessary locally for bioenergy sustainability. At the same time, other experts argue that the criteria have strong weaknesses, as they do not focus on broader sustainability issues (e.g., ensuring food security) [38]. The reason for such disagreement is that the international certifications do not go into country specific details to address their current legal, cultural, environmental and social circumstances. Despite the sustainability standards ensured by those certifications not addressing all aspects, Diaz-Chavez [38] argues that they are still important for developing sustainable agriculture and forestry.

The EU has a specific certification for biofuels and bioliquids. These voluntary schemes, recognised by the European Commission, check the type of land the biofuel has been produced from, ensures a sufficient level of greenhouse gas emissions have been saved (at least

50 % and 60 % for new biofuels and bioliquids production plants, respectively), and that soil, water, air and social criteria have been protected [51]. However, sustainability standards for biomass-for-energy purposes are still under development. Some countries have deployed national sustainability schemes for solid biomass to be able to determine whether certain bioenergy projects are eligible for renewable energy subsidies. However, they often lack validity for imported biomass [184]. Sustainability of imported solid biomass is then ensured via globally applicable schemes or standards, such as Forest Stewardship Council (FSC), International Sustainability and Carbon Certification (ISCC) or NTA 8080 certification system [162]. Unfortunately, these standards still might not provide the sufficient protection. Work by Meyer & Priess [151] propose rather a development of new indicator sets, which apart from combining several certification schemes would also include the social and economic impacts. However, development of such certification schemes would be facing a number of issues related to uncertainties in terms of the feasibility, implementation, costs and compliance with international trade law [229]. Therefore, national sourcing of biomass and proposing robust biomass sustainability standards specific for the location is the most reliable way to ensure the required environmental benefit is really achieved.

5.1.3 Reduction in long-distance bulk transport

Strategic utilisation of regional biomass could significantly decrease the biomass transportation distances [18]. Reducing the transported distance could cut costs as well as emissions associated with bioenergy deployment, but the extent of the impact highly depends on the bioenergy supply conditions. For example, a study by Handler *et al.* [92] estimates that forest biomass harvesting, loading and transport generates in total 40.4 kgCO_2eq for every green tonne, with transport accounting for half of the emissions. On the other hand, study by Zhang *et al.* [257] defines harvesting as a higher contributor to the total greenhouse gas emissions of biomass production than transportation. In addition to supply conditions, different means of transport play a large role. For example, transport by trucks could be up to five times more emission intensive per tonne-mile than transport by rail [92]. Selection of ship transport could reduce the emission intensity of biomass transport even further [18]. Chen *et al.* [29] even point out the impact of the logistic scenarios and the emission reduction when biomass is transported on paved highways instead of dirt roads.

The impact of biomass transport could be reduced by biomass densification or by its conversion to the final product closer to the biomass origin. For example, a case of biofuel supply to California from Illinois shows the most economical transport is by initial local conversion of biomass to ethanol [131]. Therefore, strategic biomass pre-processing can improve the system. This can be particularly experienced at places with high biomass spatial distribution density as relatively concentrated area could significantly reduce the biomass transport work [81]. Similarly in-forest biomass handling plays an important role and the deeper it is necessary to go into the forest, the greater environmental impact could be expected [29]. Hence, biomass transportation should be efficient and effective, as otherwise the natural advantage of local biomass supply might be lost over long-distance transport. Generally though, studies show that biomass transportation, even long-distance, does not significantly impact the environmental benefit of biomass as a whole [92].

5.2 Identifying the most suitable locations

The benefits of deployment of local bioenergy systems are not guaranteed and depend on multiple factors, which often are not correlated with each other. This makes certain locations more suitable for the deployment of specific bioenergy systems than others. So far, there exist only a very limited number of studies, which are specifically looking into whether bioenergy should be used for a particular purpose at the given location. Especially when considering national strategies and focusing on the problem from a global perspective. The gap shows the need to develop an objective and quantifiable method for assessing the suitability of biomass for a specific sector in each country. The present work has developed a methodology particularly for the steel sector, which is able to give an additional insight into which countries should deploy bioenergy into their iron and steel industry, not just because it is economically viable and environmentally appealing option, but also because such solution is suitable and hence there are maximum chances that it would benefit the local economy. Suitability means satisfying a range of conflicting criteria. For this purpose, multi-criteria analysis has been deployed in the present work to provide evidence for energy planning decision making. The next section provides a brief summary of existing multi-criteria analysis models.

5.2.1 Existing multi-criteria assessment models

Multi-criteria analysis is a common assessment for renewable energy technologies, to compare their sustainability and suitability for a given location. In general, the studies deploy such models in two ways: to find the best renewable energy technology for a specific location or to identify the most suitable location for a specific renewable energy technology.

An example of the first is in work done by Troldborg *et al.* [218], which evaluates the suitability of different renewable technologies for Scotland based on technical, environmental and socio-economic criteria. An example of the latter is in the work by Watson & Hudson [239], which compares the suitability of wind and solar farms across an area in the South of England.

Assessing suitability of bioenergy is slightly different to the studies discussed above as biomass, unlike for example wind or solar radiation, could be transported for long distances, including overseas. The previous section discussed the extra advantages of sourcing biomass locally. Therefore, this study assesses suitability of bioenergy under a constraint that it would be sourced solely domestically. Previous models used to assess bioenergy systems can be categorised as:

- **Optimisation methods** – select the best available option out a list of alternatives;
- **Predictive models** – give list of possible renewable energies which should be deployed based on the evaluation of future scenarios;
- **Qualitative study methods** – present conclusions based on interviews, surveys or focus groups;
- **Others** – include conclusions made based on life-cycle analysis and geographical information systems [199].

Generally, the optimisation methods are the most popular, which example is the PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluations) used previously to rank, e.g., biomass collection and transportation systems [122].

The suitability of a bioenergy system also depends on the final goal aimed to achieve and hence the interest of the study. The majority of the studies have used these models to perform technology selection, e.g., to identify the most suitable conversion facility technology, followed by studies focusing on political and legal issues related to biomass deployment [199]. Interestingly, most suitability studies are focusing on Europe [199], which could indicate Europe's high motivation for the strategic use of the limited biomass resources. Troldborg *et al.* [218] point out the high uncertainty of those assessments due to the wide area they cover and suggest those assessments should be rather site-specific. However, governmental decisions about renewable energy deployment are mostly done on regional or even country level and therefore there is a need for suitability assessment models on such scale, despite the uncertainty of the findings.

5.2.2 Case of bioenergy for iron and steelmaking

One of the large-scale suitability assessment problems is to identify whether the EU has suitable opportunities for bioenergy deployment within its iron and steelmaking industry. A possible approach is to compare the suitability of the EU-28 countries with countries around the world. This has led the present author to the development of a suitability assessment, which is able to do a comparison on the global level and takes into consideration various aspects required for successful integration of bioenergy into the iron and steel industry.

5.3 Global Suitability Index

To compare the opportunities for bioenergy deployment across the world top 40 steel producing countries via BF-BOF route, the present study developed a *Global Suitability Index* (GSI). The index takes into consideration countries' steel production status, relative amount of biomass resources and the general governmental support for diverting from fossil fuel use. This section provides an overview of the methodology.

5.3.1 Methodology development

The development of the GSI is based on the methodology used in other suitability assessment models, which have been already widely deployed to define suitability of an ecosystem for a certain specie (the Habitat Suitability Index [73]), fitness of land for specific use (the Land Suitability Index [143]) or security of energy generation (the World Energy Trilemma Index [247]). The GSI adopts certain approach from each one.

The idea of grouping variables into sub-indicators is within the GSI adopted from the Habitat Suitability Index (HSI). The HSI has been widely deployed to assess the existing habitat conditions for the studied species within a specific ecosystem by measuring how well each environmental variable meets the species' habitat requirements [73]. The fitness is expressed using suitability graphs, which shape is based on literature, professional judgement, lab studies and/or field observations. The variety of the variables and a gap in the literature on this topic does not allow similar approach to be undertaken within the GSI. Instead, the GSI uses a methodology deployed within the World Energy Trilemma Index [247], which ranks countries in terms of their likelihood to provide sustainable energy policies. The World Energy Trilemma Index takes into consideration three dimensions: energy security, energy equity and environmental sustainability [247] (similarly as the GSI considers steel production, bioenergy and policy explained later in Section 5.3.2).

Representable variables are chosen for each dimension, where the obtained values for all countries are normalised to a standard scale 0-10, where 10 is the maximum. The World Energy Trilemma Index then ranks the countries based on their performance in each dimension, as well as in terms of their final index. Application of this approach within the GSI eliminates the need to define the suitability requirements, as in the case of the HSI. Defining meaning of each score given within the GSI is based on the Land Suitability Index (LSI) [143]. The LSI focuses on the suitability of the physical, biological and functional environment for the given land use change. Figure 5.1 summarises the desirable and unsuitable features of each of the model for the general GSI development.

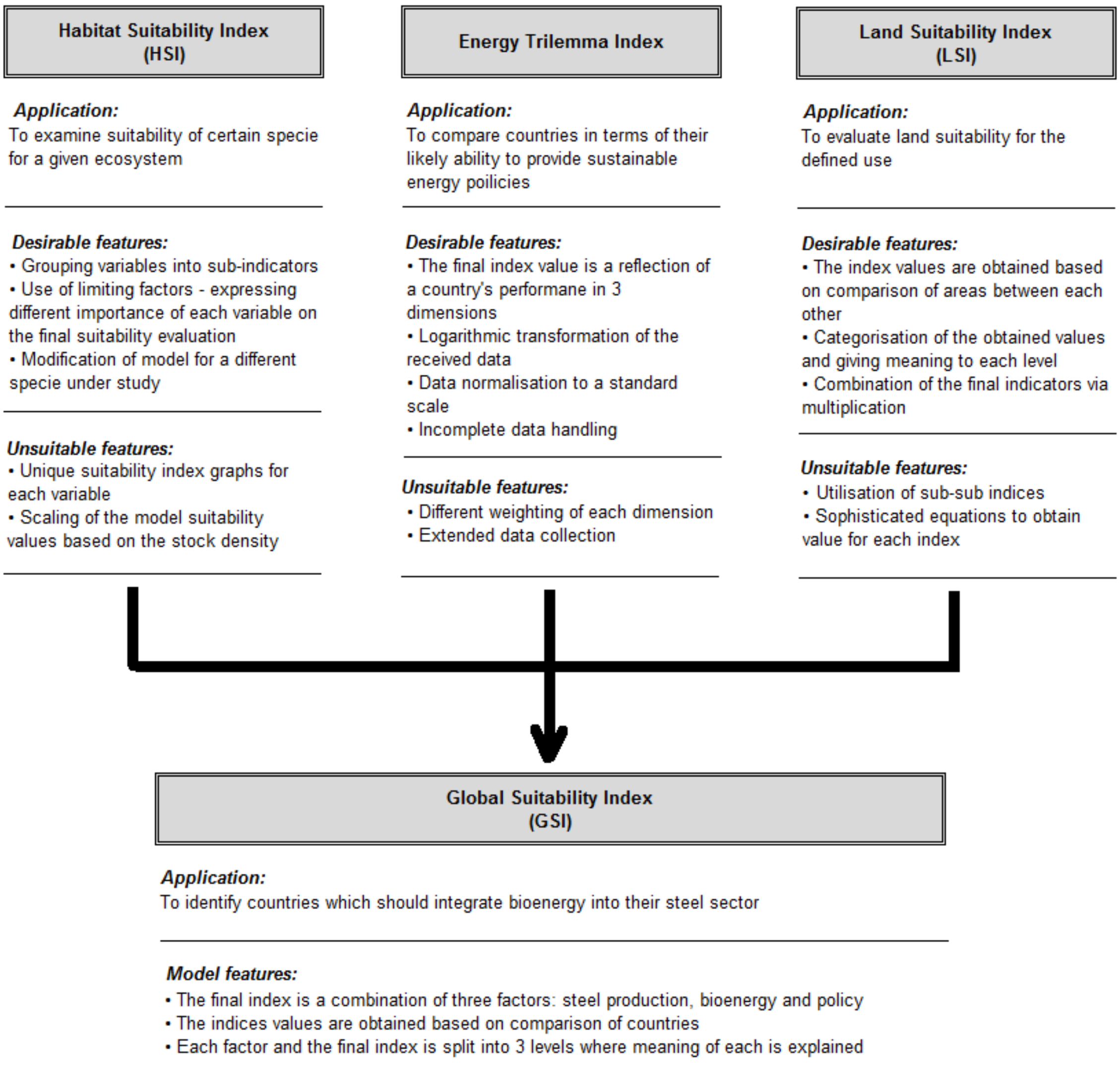


Figure 5.1: Schematic diagram representing the adopted and omitted features taken from other suitability assessment models considered during the development of the GSI.

5.3.2 Development of sub-indices

The suitability of bioenergy deployment within a country's iron and steelmaking industry, expressed by the GSI, depends on its performance across various aspects. Such performance is expressed in the present work by a score ranging between 0 and 3, where values closer to 3 represent a country having a leading status and values closer to 0 its low status. This study focuses specifically on three aspects: country steel production status, relative size of sustainable bioenergy resources and motivation of the government to use alternative fuels. Within the GSI, these aspects are addressed as the study factors. In detail,

- **Steel production factor** measures the current and potential steel production of each country. Its categories indicate insignificant (values between 0 and 1), significant (values between 1 and 2) and outstanding (values between 2 and 3) opportunities for the BF-BOF iron and steel production route;

- **Bioenergy factor** identifies the amount of domestic biomass resources relative to the amount of steel produced via the BF-BOF route in the country. Categories again indicate insufficient (values between 0 and 1), sufficient (values between 1 and 2) and excess (values between 2 and 3) sustainable biomass resources;

- **Policy factor** evaluates the governmental ability and motivation to support the use of alternative fuels through legislation and recycling rates. Either low (values between 0 and 1), average (values between 1 and 2) or high (values between 2 and 3) governmental incentive for alternative fuels is defined.

Each of the listed factors is treated as sub-index of the final index, as shown in Figure 5.2. The mathematical transformations to obtaining each factor are described below.

Steel production factor

The steel production factor is a combination of variables that define the current and prospective future of steel production via BF-BOF route within the studied country. Previous research, described in detail in the Appendix A (taken directly from the publication by Mandova *et al.* [138]) has identified six key variables that should be considered when studying such topic:

- Economic growth (V_1) – represents the economic growth of the country over the past 5 years (GDP growth expressed as average annual % over years 2010 to 2014 [213])

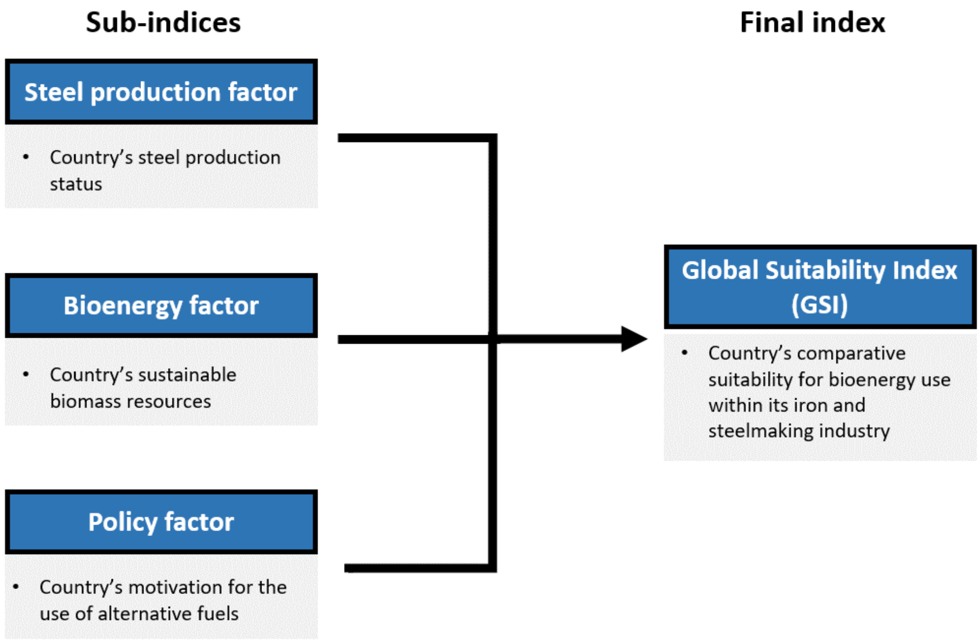


Figure 5.2: GSI structure, representing the three sub-indices leading into the final index.

- Coking coal consumption (V_2) – reflects the amount of coking coal consumed in the studied country (in kt in 2015) [101]
- Steel production via BF-BOF route (V_3) – indicates the amount of steel produced via BF-BOF route (in kt in 2014) [251]
- Total steel production (V_4) – expresses the country's total amount of steel produced (in kt in 2014) [251]
- Apparent steel use (V_5) – indicates the demand for steel in the country (in kt of crude steel equivalent in 2014) [251]
- Proportion via BF-BOF (V_6) – expresses the significance of BF-BOF route for the steel production in the country (in % of total crude steel production in 2014) [251]

First, comparative value is required for each of the listed variable V_k, where $k = 1, 2, \ldots 6$, above. The values are transformed to a scale between 0 and 3 based on how the specific country is performing in the corresponding variable. As the range of the values for variables V_2, V_3, V_4 and V_5 is very large, they are transformed using a logarithmic, rather than a linear, scaling. The sub-indicator value $S_{k,i}$ is hence obtained using one of the following equations:

$$S_{k,i} = 3 \times \left(\frac{V_{k,i} - V_{k,min}}{V_{k,max} - V_{k,min}} \right) \qquad \text{for} \qquad k = 1, 6 \tag{5.1a}$$

$$S_{k,i} = 3 \times \left(\frac{\log V_{k,i} - \log V_{k,min}}{\log V_{k,max} - \log V_{k,min}} \right) \qquad \text{for} \qquad k = 2, \ldots, 5 \tag{5.1b}$$

for each country i, where $i = 1, 2, \ldots 40$. Specifically, $V_{k,min}$ and $V_{k,max}$ are the minimum and maximum values of the variable V_k. $V_{k,i}$ is the value collected for the variable V_k and for the specific country i under study. Equations in 5.1 hence assign 0 to the country with the lowest value for the specific variable, 3 for the country with the highest value, and distribute values between 0 and 3 for all other studied countries. This procedure is represented as step 1 in Figure 5.3.

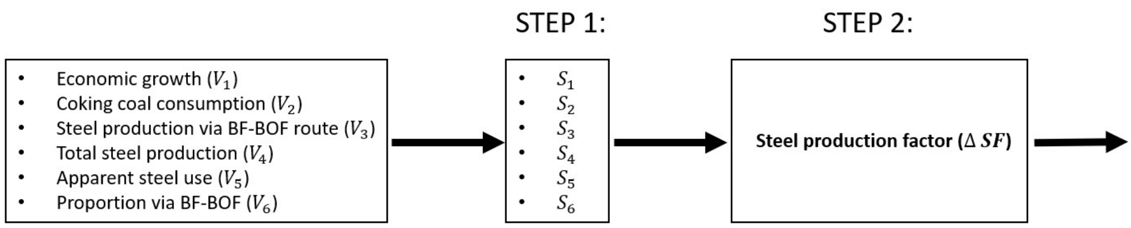


Figure 5.3: Steps proceeded to obtain the steel production factor.

After the scaled values for each variable are obtained using Equation 5.1, the studied variables have to be combined to produce steel production factor ΔSF, step 2 in Figure 5.3. It is assumed that all of the listed variables have the same importance, hence steel production factor ΔSF is obtained just by averaging the calculated values $S_{k,i}$ ($k = 1, 2, \ldots 6$) for each country i:

$$\Delta SF_i = \frac{\sum_k S_{k,i}}{6} \qquad \text{for} \qquad k = 1, 2, \ldots, 6, \quad i = 1, 2, \ldots, 40. \tag{5.2}$$

The country's value of ΔSF_i is its score for the steel production factor.

Bioenergy factor

Variables considered for the bioenergy factor are chosen to provide comparison of the amount of national biomass resources across the studied countries. Previous studies listed a large range of biomass that can be considered for ironmaking. This includes biomass from forestry as well as agriculture, which can be produced through crop harvesting specifically for the iron and steelmaking production purposes or in the form of residues resulting from biomass production for other purposes. Chapter 3 and 4 have focused only on woody biomass, as only the properties of woody biomass allow higher percentage of fossil fuel substitution. On the other hand, using biomass from agriculture could still achieve notable emission reduction across an integrated steel plant, and therefore agricultural biomass is also considered in this chapter.

For agricultural as well as forestry biomass, this work recognises its production via primary and secondary route. The primary route estimates are obtained based on the size of country's cultivated land and forest land – which excludes protected forests. Also, the area of forest land is halved if forest protection legislation is not proposed in the country, to ensure sustainability. In terms of biomass stream from the secondary production, this work considers the wood processing co-products, including wood waste and scrap not useable as timber. In terms of agriculture, comparison of residues from producing barley [254], coconuts [144], ground-nuts [254], oats [254], rapeseed [254], rice [30, 42], rye [254], sugarcane [42], sunflower seed [169, 254] and wheat [254]. The estimated residue amount is obtained from their total yearly production for each specific country and scaled using the corresponding harvest index (amount of residue generated from producing 1 kg of a crop) for each crop.

Overall, the information on biomass production within each country is represented using five variables:

- Forest protection legislation (V_7) – ensures the country has legislations and regulations supporting sustainable forest management at national and regional level (2014 data [67]);
- Forest area excluding protected area (V_8) – represents the potentially available forest area (expressed in 1000 ha using 2015 data [67])
- Wood residue (V_9) – sums the amount of forest residue produced (in m^3 using 2014 statistics [65])
- Agricultural area (V_{10}) – represents the amount of arable land (expressed in 1000 ha using 2013 statistics [213])
- Agricultural residue (V_{11}) – represents the amount of agricultural residues produced in a year (expressed in tonne using 2014 statistics [66])

The bioenergy factor is obtained in three steps, as shown in Figure 5.4. In step 1, the initial variables V_k, where $k = 8, \ldots 11$, are first scaled by the variable quantifying the steel

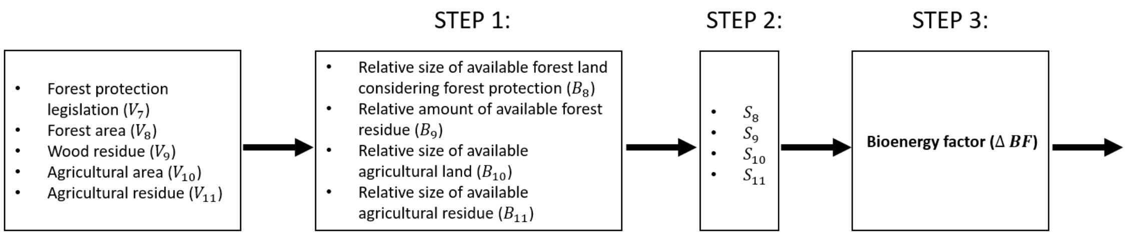


Figure 5.4: Steps proceeded to obtain the bioenergy factor.

production through BF-BOF route (V_3), to obtain indication of their size relative to the size of their steel industry. The relative sizes of each variable are expressed using variable B_k (where $k = 8, \ldots, 11$). To ensure sustainable biomass production, binary variable V_7 is used to halve the amount of the considered forest land (variable V_8) if a country does not have strong forest protection legislation. Step 1 in Figure 5.4 is hence obtained using equations defined below:

$$B_k = \frac{(0.5 + 0.5 \times V_7) \times V_k}{V_3} \qquad \text{for} \qquad k = 8 \tag{5.3a}$$

$$B_k = \frac{V_k}{V_3} \qquad \text{for} \qquad k = 9, 10, 11. \tag{5.3b}$$

Step 2 within Figure 5.4 requires further scaling of each variable to give each country a comparable number between 0 and 3, same as step 1 within the steel production factor. The used formula is hence on the same basis as Equation 5.1, however as some values are close to 1, small adjustment within the formula is performed to prevent obtaining large negative values:

$$S_{k,i} = 3 \times \left(\frac{\log(B_{k,i} + 1) - \log(B_{k,min} + 1)}{\log(B_{k,max} + 1) - \log(B_{k,min} + 1)} \right) \qquad \text{for} \qquad k = 8, \ldots, 11. \tag{5.4}$$

Here, $B_{k,min}$ and $B_{k,max}$ are again the minimum and maximum values for the scaled variable B_k. $S_{k,i}$ is the scaled value for each variable used for bioenergy factor within a specific country i (step 2 in Figure 5.4).

As country's strong dominance in forestry does not necessarily mean its strong dominance in agriculture and vice versa, the present work scores countries based on their strongest biomass industry. In detail, the bioenergy factor ΔBF, step 3 shown in Figure 5.4, is obtained by taking only the maximum value from the area and the residue:

$$\Delta BF_i = \frac{\max(S_{8,i}, S_{10,i}) + \max(S_{9,i}, S_{11,i})}{2}, \qquad \text{for} \qquad i = 1, 2, \ldots, 40. \qquad (5.5)$$

Policy factor

Variables selected for this factor are aiming to represent the country's incentive to use alternative fuels. This is reflected by country's attitude towards a circular economy, its reliance on imported fossil fuels, the contribution of steel sector to country's greenhouse gas emissions and the government's capability to support the fuel switch. All those factors are represented by five variables:

- Reliance on imported coking coal (V_{12}) – expresses the motivation for decreasing country's reliance on imported fuels (represented as ratio of the amount of coking coal imported over the amount of coking coal consumed [101])
- Contribution to the total GHG emissions (V_{13}) – expresses the national motivation to decarbonize their BF-BOF steel production route (in % of total GHG emissions estimated using data from [123, 248, 251])
- Circular economy motivation (V_{14}) – indicates country's attitude for keeping resources in the economy (represented as landfill rate in kg per capita using 2014 data [59, 98, 227])
- Strength in policy proposals (V_{15}) – indicates the quality of policy formulation and implementation (represented using governmental effectiveness 2014 data [214])
- Governmental support for development (V_{16}) – indicates the ability of the government to promote private sector development (represented using regulatory quality 2014 data [214])

The steps to obtain the policy factor values from those variables are shown in Figure 5.5.

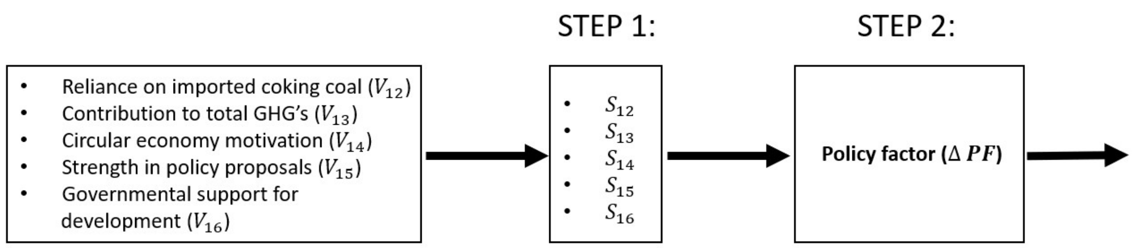


Figure 5.5: Steps proceeded to obtain the policy factor.

As previously done for the steel production and bioenergy factor, the policy factor variables are first transformed into values between 0 and 3 (step 1 in Figure 5.5). Linear transformation is used, however inverted linear transformation is applied for variable V_{14} as higher landfill rate indicates country's low attitude for efficient use of resources. The specific equations used for the transformation are:

$$S_{k,i} = 3 \times \left(\frac{V_{k,i} - V_{k,min}}{V_{k,max} - V_{k,min}} \right) \qquad \text{for} \qquad k = 12, 13, 15 \text{ and } 16,$$
$$S_{k,i} = 3 \times \left(1 - \frac{V_{14,i} - V_{14,min}}{V_{14,max} - V_{14,min}} \right) \qquad \text{for} \qquad k = 14.$$

All the transformed values $S_{k,i}$, where $k = 12, \ldots, 16$ and $i = 1, 2, \ldots 40$ are then combined into one, called policy factor ΔPF, where each variable is treated with equal importance. This is represented as step 2 in Figure 5.5 and done using equation:

$$\Delta PF_i = \frac{\sum_k S_{k,i}}{5} \qquad \text{for} \qquad k = 12, \ldots, 16, \quad i = 1, 2, \ldots, 40. \tag{5.7}$$

5.3.3 Final Index

The steel production, bioenergy and policy factors are combined to produce the final Global Suitability Index, as shown in Figure 5.6. All of the three sub-indices have the same importance, as it is assumed that only a country performing well across all of the listed factors present a potential for successful integration of bioenergy into the steelmaking process. The three factors are multiplied with each other, rather than added, to rank higher a country which is doing reasonably well across all indicators above a country which scores very well in one indicator and bad in an another one:

$$\Delta_i = \Delta SF_i \times \Delta BF_i \times \Delta PF_i. \tag{5.8}$$

This is defined as step 1 in Figure 5.6.

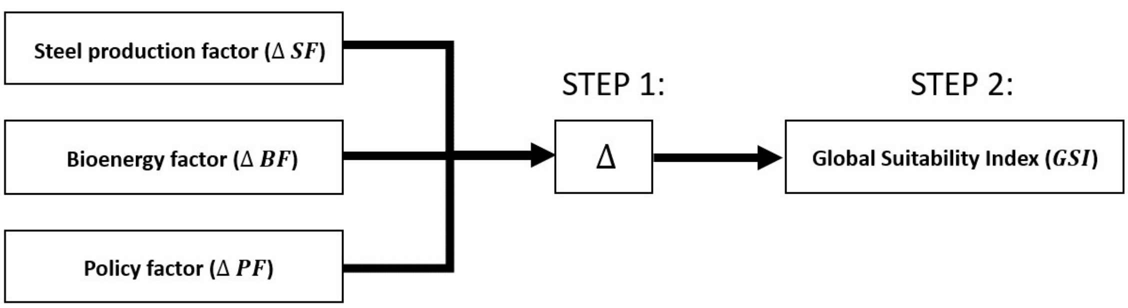


Figure 5.6: Final steps proceeded to produce the GSI for each country.

The final GSI value for each country is hence obtained by linearly re-scaling the obtained values of $\mathit{\Delta}_i$ to a scale 0 to 3. This is shown in Figure 5.6 as step 2 and done using the equation:

$$GSI_i = 3 \times \left(\frac{\mathit{\Delta}_i - \mathit{\Delta}_{\text{min}}}{\mathit{\Delta}_{\text{max}} - \mathit{\Delta}_{\text{min}}} \right), \qquad \text{for} \qquad i = 1, 2, \ldots, 40, \tag{5.9}$$

where $\mathit{\Delta}_{\text{min}}$ and $\mathit{\Delta}_{\text{max}}$ are the values of countries which by multiplying their indicators achieved the smallest and largest values from all of them respectively.

5.4 Results and discussion

Values obtained for the final GSI, as well as for each of the sub-index, are presented in Table 5.1. In total, top 40 steel producing countries via BF-BOF are considered for this analysis. Other countries either do not produce steel via the BF-BOF route at all or their production is negligible.

Based on the obtained results, this section gives insight into which EU countries are the most suitable to deploy bioenergy into their iron and steelmaking process, as they offer a co-location of significant iron and steel industry, sufficient biomass resources and supportive policies. Each of those aspects are discussed first on their own, followed by a conclusion on the overall suitability.

5.4.1 Small significance of EU steel production on the global market

The results of the steel production factor indicate a relatively low dominance of the individual EU countries on the global steel production market, but some EU countries still present significant opportunities for the blast furnace ironmaking. From Figure 5.7 and Table 5.1 it can be observed that none of the EU countries obtained a score within the steel production factor between 2 and 3. The highest scoring EU country is Germany (value 1.6) followed by the UK (value 1.4), Poland, France, Czech Republic, the Netherlands and Austria (all with values around 1.3). With Germany being the only EU country scoring above 1.5 shows the limited opportunities of individual EU countries for primary steel production via the BF-BOF route, when those opportunities are compared to the rest of the world. On the other hand, only 8 other countries outside the EU score above 1.5. These are Brazil, China, India, Japan, Russia, South Korea, Taiwan and the US, out of which only China and India achieve score above 2. Interestingly even Japan, the second biggest crude steel producer via BF-BOF route in the world [252], receives a score below 2. This indicates that only a handful of countries around the world, and possibly only

Table 5.1: Results obtained for the steel production, bioenergy and policy factor as well as the final GSI index. Highlighted values in blue indicate countries scored in the highest category.

	Steel production factor	Bioenergy factor	Policy factor	GSI
EU-28 countries				
Austria	1.3	1.2	**2.7**	1.9
Belgium	1.1	0.9	**2.5**	1.1
Czech Republic	1.3	1.0	**2.1**	1.3
Finland	0.9	**2.0**	**2.6**	**2.1**
France	1.3	1.7	**2.2**	**2.3**
Germany	1.6	1.0	**2.5**	1.9
Hungary	0.9	1.4	1.8	1.1
Italy	1.1	1.1	**2.0**	1.1
Netherlands	1.3	0.9	**2.5**	1.3
Poland	1.3	1.7	**2.0**	**2.1**
Romania	0.7	1.9	1.7	1.1
Slovakia	1.3	1.0	**2.3**	1.3
Spain	1.0	1.7	**2.1**	1.6
Sweden	1.1	**2.1**	**2.8**	**2.9**
United Kingdom	1.4	1.0	**2.3**	1.5
Other countries				
Algeria	1.0	**2.2**	0.5	0.5
Argentina	1.1	**2.3**	1.2	1.4
Australia	1.3	**2.6**	1.4	**2.1**
Bosnia and Herzegovina	0.9	1.0	1.3	0.5
Brazil	1.7	1.9	1.3	**2.0**
Canada	1.3	**2.4**	**2.0**	**3.0**
Chile	1.0	**2.4**	1.8	1.9
China	**2.9**	1.0	1.9	**2.6**
Colombia	0.8	**2.8**	1.5	1.6
Egypt	0.7	1.8	1.1	0.6
India	**2.0**	1.4	1.5	1.9
Iran	0.9	1.6	1.1	0.7
Japan	1.9	0.8	**2.6**	1.9
Kazakhstan	1.5	1.9	1.1	1.5
Mexico	1.3	1.3	1.6	1.2
New Zealand	0.6	1.5	1.5	0.6
Russia	1.9	1.7	1.3	**2.0**
Serbia	0.7	**2.1**	1.1	0.7
South Africa	1.2	1.8	1.7	1.7
South Korea	1.9	0.2	**2.5**	0.4
Taiwan	1.6	0.0	**2.5**	0.0
Turkey	1.5	1.2	1.8	1.5
Ukraine	1.4	1.0	1.5	0.9
United States	1.6	1.8	1.8	**2.5**
Vietnam	1.0	**2.0**	1.2	1.1

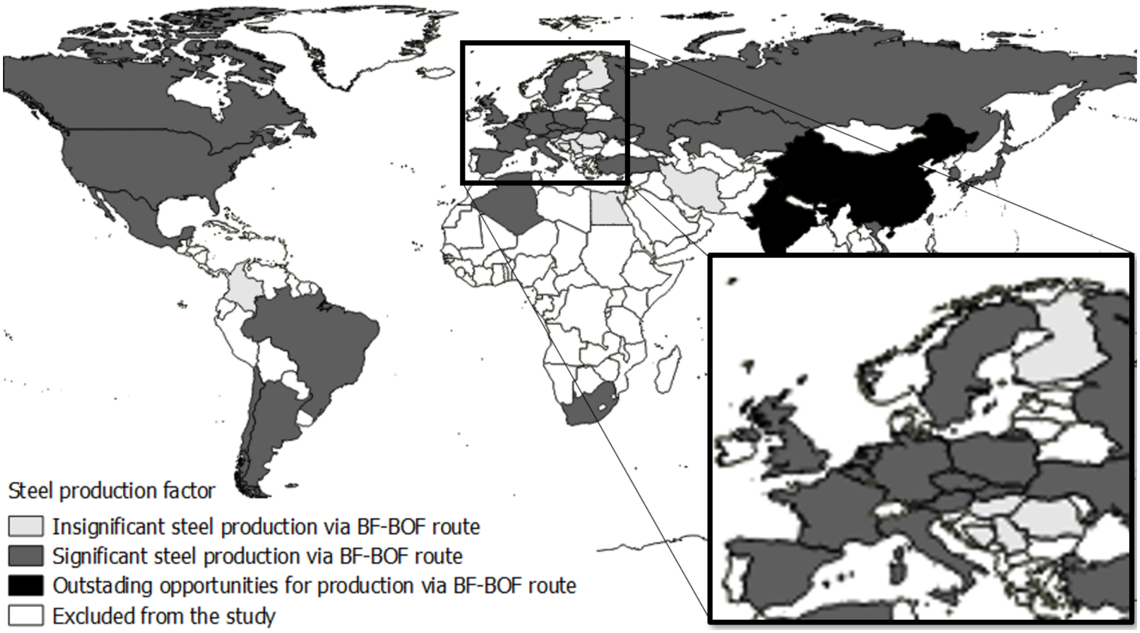


Figure 5.7: Graphical representation of results obtained for steel production factor. Figure modified from [138].

Germany in the EU, present opportunities that would guarantee long term iron and steel production via BF-BOF route in the future. Therefore, even though iron and steel making in Europe significantly contributes to the total emissions, it's long term viability might be questioned. This is despite the EU's efforts to protect the iron and steel industry due to its large importance for the EU economy (for example, due to providing thousands of jobs [86]) and the anticipated significance of primary steel production route until at least 2050 [175].

Focusing specifically on the EU countries, a high correlation between their ranking based on the amount of steel they produce via BF-BOF route and the obtained steel production factor values is observed. As Figure 5.8 shows, half of the countries are in the same position (or varied across maximum two positions) between the two rankings. In 2016, the leading steel producing countries via BF-BOF were Germany (29.5 Mt of crude steel), France (9.5 Mt of crude steel), Netherlands (6.8 Mt of crude steel), Austria (6.8 Mt of crude steel) followed by the UK (6.2 Mt of crude steel), Italy (5.7 Mt of crude steel) and Belgium (5.3 Mt of crude steel) [252]. Out of the listed countries, it is only the Netherlands, Austria and Italy, which are ranked based on the steel production factor much lower than in the ranking based on the amount of steel they produced. The lower score of the Netherlands and Austria within the steel production factor is a result of low performance in the economic growth variable and apparent steel use. For Italy, it is

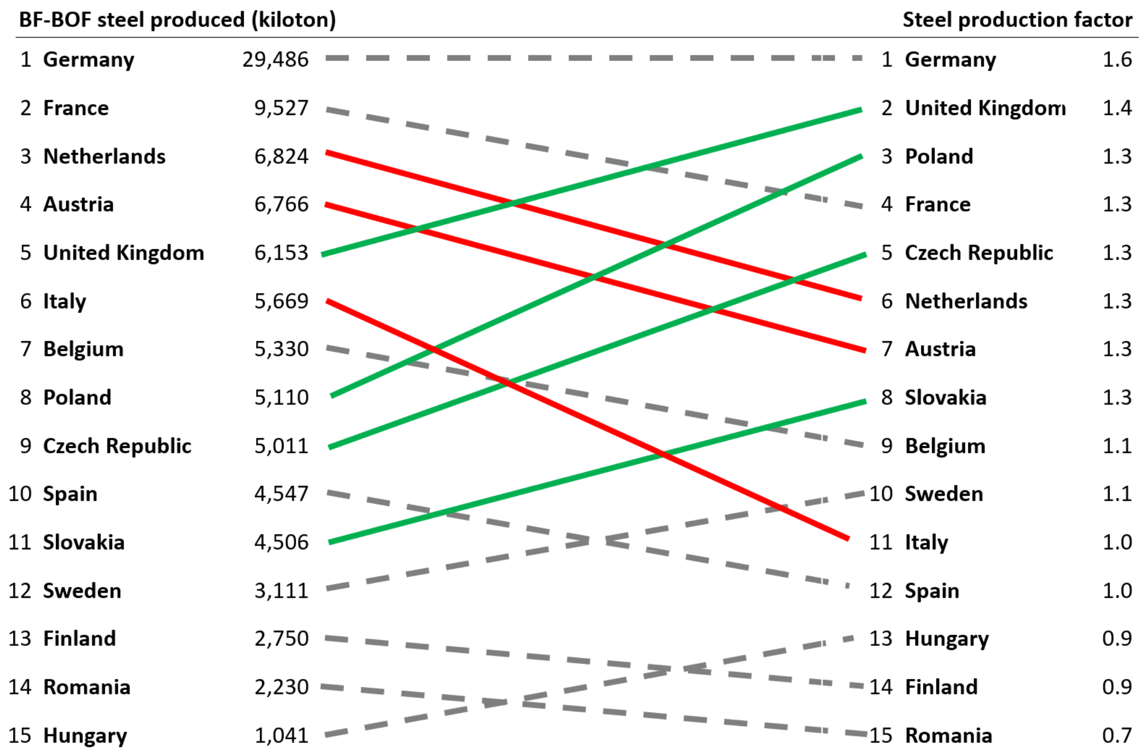


Figure 5.8: Comparison of ranking of EU countries based on the amount of steel produced via BF-BOF route [252] and their steel production factor values. Grey lines indicate small change in the ranking (two positions or less). Red and green lines indicate country's ranking in steel production factor is substantially lower or higher than in the amount of steel produced, respectively.

mainly due to a relatively low economic growth. On the other hand, the UK, Poland, Czech Republic and Slovakia ranked higher in the steel production factor, whilst also achieving high values for the coking coal consumption variable. This could indicate their tradition in the iron and steelmaking via BF-BOF route and hence higher efforts to preserve the industry. It is also important to point out the leading position of Germany across both rankings, reassuring its dominance in steelmaking via BF-BOF route in the EU now, and is expected to be in the future.

5.4.2 Sufficient bioenergy opportunities in certain EU countries

Out of the 15 EU countries producing steel via BF-BOF route, only Sweden and Finland are identified with a potential to source biomass in an excessive amount for their iron and steelmaking plants. However, as Figure 5.9 demonstrates, other EU countries could also have sufficient amount of biomass resources for bioenergy deployment within their iron and steel industry. In detail, Romania's score in the bioenergy factor is just on the borderline

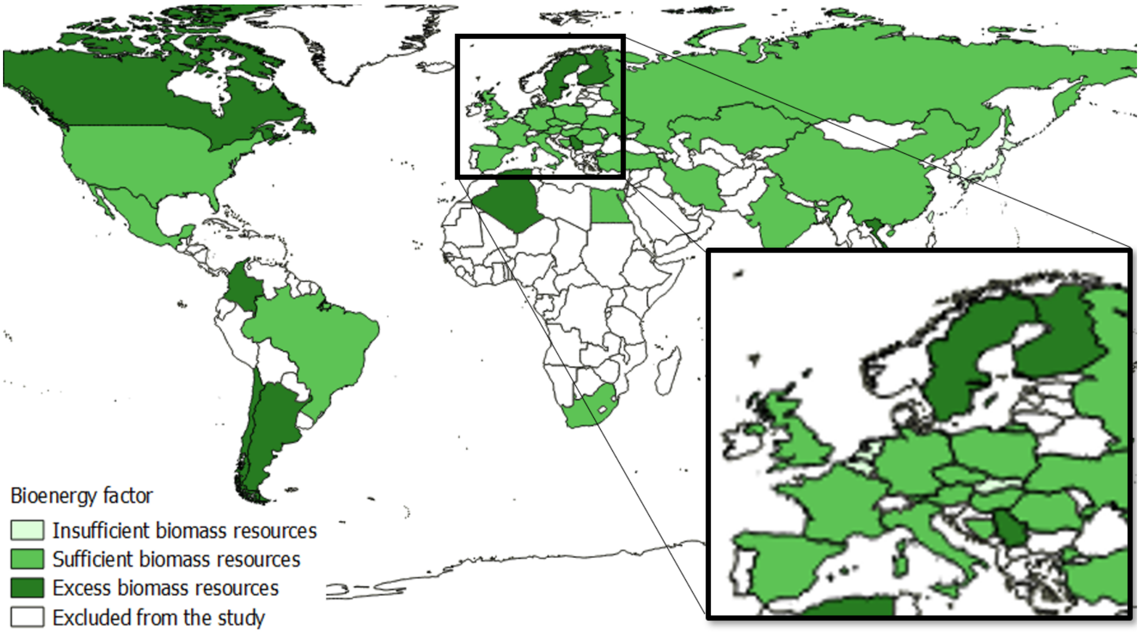


Figure 5.9: Graphical representation of results obtained for bioenergy factor. Figure modified from [138].

(1.9) followed by France, Poland and Spain (all with bioenergy factor score 1.7). On the other hand, Belgium and the Netherlands achieve score 0.9, which points out that they would not be able to source the required amount of biomass for the iron and steelmaking application domestically. The Czech Republic, Germany, Slovakia and the UK are also just on the border line between insufficient and sufficient biomass resources, with score 1.0, which points out that those countries might also find it challenging to source the required amount nationally.

Comparing the bioenergy factor results of the EU countries with the rest of the world, it can be observed that the world leading opportunities – from the bioenergy resource perspective – are in Colombia, Australia, Canada and Chile. As the measure is relative to the amount of steel they produce via the BF-BOF route, a high score could potentially indicate low steel production for some of them, resulting in only a small biomass demand. Also, the bioenergy factor focuses only on the total amount of biomass resources the country has or produces, and does not take into consideration that those resources might not be fully available due to already being used in different applications. This is a main drawback of the index, however, the motivation for the GSI development is to assess suitability, not availability. In other words, the purpose of the GSI is to provide methodology that can simply assess the capabilities of the country for fuel switching in a sector of interest, whilst being able to compare the capabilities for different countries and identify the potential barriers. To assess the actual quantity of available biomass for steelmaking, as done for example by Voivontas *et al.* [235], a very detailed data would have to be collected. This would, however, contradict the purpose of the GSI aimed for doing quick evaluations. Likewise, it can be argued that the biomass is tradable commodity and focusing only on national biomass sourcing is insufficient. Figure 5.9 indicates that trade opportunities (e.g., from Canada to EU or from Sweden and Finland to other EU countries) would be possible, where countries with excess biomass resources support countries with comparably lesser amounts. However, as previously mentioned, the purpose of this work is to evaluate opportunities for sourcing biomass domestically.

The bioenergy factor values agree with previous findings on biomass availability presented in Chapter 3. In detail, findings from Section 3.5.1 demonstrate that the top two EU countries within the bioenergy factor, Sweden and Finland, would supply 100 % of its biomass for the iron and steelmaking domestically (see Figure 3.10(b)). The alliance between the two present studies is also shown for the next three countries in terms of the given score within the bioenergy factor, Romania, France and Poland, where the previous results using the *BeWhere EU – iron & steel* model also suggest that the demand by their integrated steel plants could be met purely by domestic resources. On the other hand, the *BeWhere EU – iron & steel* defined a complete reliance on imported biomass for the Netherlands and Belgium. Both of the two countries have been classified here of insufficient domestic biomass resources. The consistency of the bioenergy factor results with the previous work presented in Section 3.5.1 demonstrates the viability of the bioenergy factor to represent the biomass status for its deployment across integrated steel plant within the studied country.

5.4.3 Strong motivation within the EU for fuel switching

The governmental motivation for using alternative fuels in the iron and steelmaking via BF-BOF route is represented using the policy factor. The obtained results are shown in Figure 5.10. The studied EU countries are leading in the policy factor, as high incentive for using alternative fuels is identified. In detail, most EU countries achieve policy factor score above 2.5, where Sweden (2.8) and Austria (2.7) score the highest. Hungary and Romania are the only two countries which do not score above 2.0 benchmark. Comparing these results worldwide, only Canada, Japan, South Korea and Taiwan score as high in the policy factor as most of the EU countries. This indicate the high motivation and support within the EU for alternative fuel switching, which could be classified as world leading.

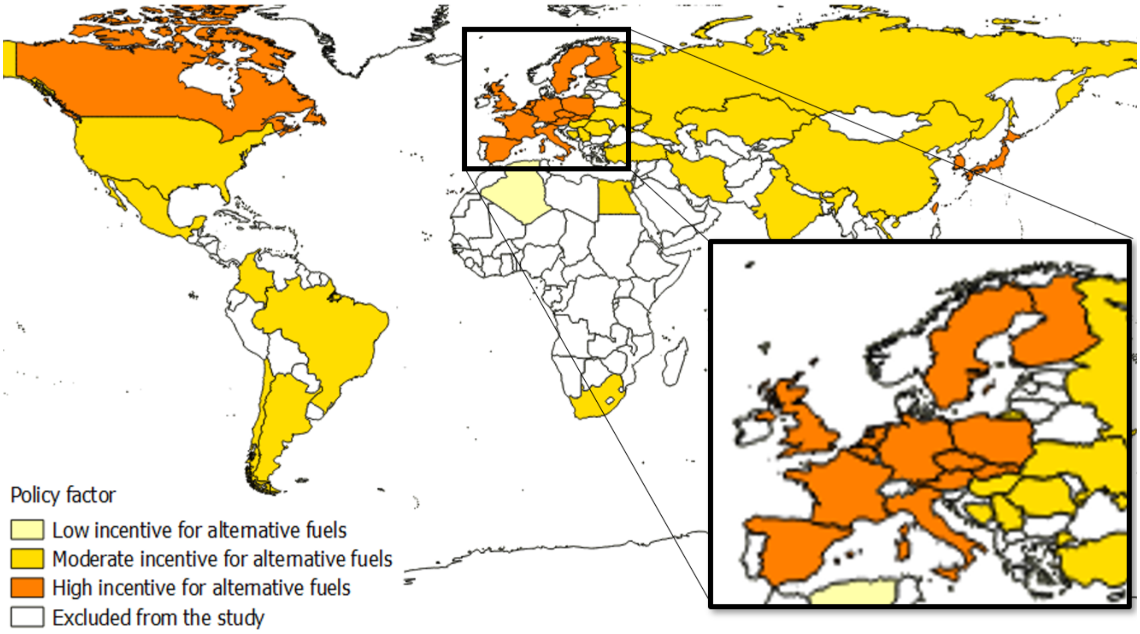


Figure 5.10: Graphical representation of the policy factor. Figure modified from [138].

It is important to ensure a full sustainability of any bioenergy system considered, including iron and steel. As the EU is lacking exact sustainability criteria for solid biomass, it is interesting to compare the policy factor results with the countries' current efforts to support sustainable biomass use. For example, Sweden has forestry management standards and most of the forest area certified. Belgium, particularly in the Flanders region, awards the number of green certificates based on the whole life cycle balance. Unfortunately, those standards so far do not apply on the imported wood. The Netherlands, on the other hand, have one of the most developed standards called the Support Sustainable Energy Production (SDE+) programme. One of the longest programmes ensuring sustainability of solid biomass is taking place in the UK, called Sustainable Forest Management (SFM) criteria [184]. Including these differences between the different national biomass sustainability criteria deployed within the policy factor would strengthen its findings.

5.4.4 Suitability of bioenergy for European iron and steel industry

Sweden and France are the EU countries which are listed between the top five countries worldwide that present the biggest potential to integrate bioenergy into their steel-making sector by the GSI. The leading country worldwide is Canada, mainly due to high scores in bioenergy and policy factors. Sweden, which takes second place, also scores high in the bioenergy and policy factors. China's third place is secured due to its world-leading

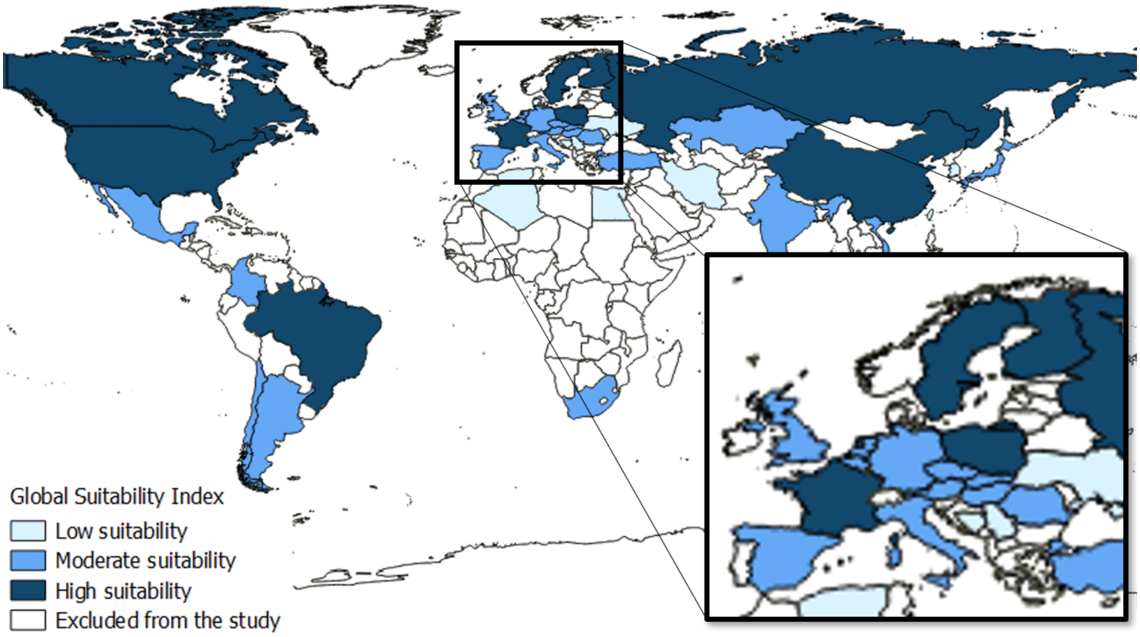


Figure 5.11: Graphical representation of the results obtained for the final GSI. Figure modified from [138].

position in the steel production. USA is ranked fourth, despite scoring above average in all indicators, but never achieving the highest score in any one of them. Fifth place for France is secured by high ranking in the policy factor and above average in bioenergy factor. Figure 5.11 graphically represents the results of the final GSI index, with a particular focus on Europe.

The high suitability of France corresponds to the previous findings in Chapter 3 and 4, as France presents one of the lowest CO_2 avoidance cost for pure biomass as well as bio-CCS case. For Sweden, the CO_2 avoidance cost is relatively high for solely biomass utilisation, but CO_2 avoidance cost using bio-CCS, estimated in Chapter 4, is relatively low when compared to the rest of the EU. This means that for both, France and Sweden, bioenergy integration within an iron and steelmaking would a strategic decision from the resource perspective, but only for France from the economic perspective as well.

Apart from Sweden and France, integration of bioenergy would be a strategic decision also for other countries, such as Finland, Poland, Germany or Austria, where the last – particularly the last two – score on the border line, achieving the GSI value of 1.9. As Table 5.1 shows, the GSI value for Finland is reduced due to its low score within the steel production factor, which points out the country's low significance on the global steel market. Similar case is for Austria and Poland. The insignificance of steel production in these countries hence might be considered as a barrier, as national and global motivation for the use of alternative fuels in this case might not be seen as a priority. On the other hand, the initial biomass substitution within those countries would be below EU's average of 27 € ${t_{CO_2}}^{-1}$, as shown in Chapter 3, which indicates a relative economic viability of bioenergy when compared to other countries. For Germany, the main issue is the lack of bioenergy resources relative to the amount of steel produced via the BF-BOF route. However, Germany is very strong in circular economy, as the policy factor shows, hence its strength in this indicator might help to overcome the low score achieved for the bioenergy indicator.

It is important to point out that the implementation of alternative fuels in the steel industry takes years during which the countries capabilities can remarkably change. These changes are not accounted within the GSI and the GSI considers only the current situation. Including predictions and scenarios projections in the GSI should be considered in the next step, which would be able to give further details and greater certainty on the suggestions provided above. At the same time, it is important to understand that the GSI values do not give a concrete classification of suitable and unsuitable, but rather an estimation that one country is more capable of successful integration of bioenergy into the sector than another country. The model reliability might be also limited due to the fact that the suitability of biomass in the steel sector for each country might be affected by multiple other factors than the ones listed above.

5.5 Chapter summary

Deployment of bioenergy within countries which present also non-economic opportunities can enhance the overall success of the technology. Within this chapter, a multi-criteria global suitability assessment, called *Global Suitability Index* (GSI), is developed to examine the status of countries' steel industry, sustainable biomass resources and supportive policies for the top 40 steel production countries via the blast furnace ironmaking route. The GSI provides a holistic comparison of countries' suitability for deployment of bioenergy within their iron and steelmaking plants, focusing mainly on the non-economic aspects.

The results highlight large differences across the EU countries in terms of suitability. First, only few countries in the world have significant steel production via BF-BOF route and the EU countries do not belong between them. The biggest potential for long term steel production via BF-BOF in the EU is in Germany. On the other hand, some EU countries have a potential to use domestically sourced biomass for such application. In particular, Sweden and Finland are demonstrating extra opportunities for sourcing locally the sufficient amount of biomass, whilst producing significant amount of steel. In general, EU countries score high in the policy factor showing the governmental support for such fuel switching might be one of the best in the world. This, however, does not mean that such support would be sufficient for its successful adaptation. Overall, the best opportunities, when only non-economic aspects are considered, are observed for Sweden and France. Previous chapters have also identified French plants as ones with the lowest CO_2 avoidance cost using biomass in Europe, which makes France one of the most suitable countries for which bioenergy deployment within iron and steelmaking would be a strategic decision from multiple perspectives.

Chapter 6

Conclusions and future work

6.1 Research summary

The 30 integrated steel plants, which produce iron and steel via BF-BOF route, are one of the biggest single-point CO_2 emitters in Europe. As a result, they are under a large pressure to decarbonise. The present work analyses reducing their emission intensity via a strategy of partial-fuel switching to bioenergy. Using energy system models, this work assesses this strategy from the biomass availability, CO_2 reduction potential and policy perspective. The overall findings are as follows:

- **The main advantage of bioenergy over other technologies is its potential to reduce a significant amount of on-site CO_2 emissions without a major retrofit of the plants**. A full – maximum technically feasible – deployment across all integrated steel plants in the EU could achieve up to 40 % CO_2 reduction, equivalent to 76.8 Mt_{CO_2} y^{-1}. Partial fuel switching to biomass is one of the BATs that do not require significant reconstruction of the existing facilities, often resulting in a long-lasting shut-down times of the impacted units. Similarly, bioenergy deployment does not require changing the nature of the deployed iron and steelmaking processes avoiding a major capital investment.
- **Biomass resources across the EU are limited and a large-scale biomass deployment within the iron and steel sector would use their significant share.** The potential demand for up to 1.1 EJ y^{-1} is equivalent to 15 % of the theoretical biomass potential in the whole of Europe. The findings demonstrate that majority of this biomass could be sourced within the EU (89 %). This would significantly limit its availability for other sectors in the future, which rely on bioenergy as a key strategy for reaching their environmental targets. Therefore, bioenergy should

not be deployed widely across all integrated steel plants, but rather as a strategically defined solution for specific plants instead.

- **The current EU-ETS carbon prices do not make bioenergy deployment economically viable.** Even though the work identifies the switching price for initial consideration of biomass as 20 € $t_{CO_2}^{-1}$ for a few plants, carbon price of 30 € $t_{CO_2}^{-1}$ would be required on average. Achieving 20 % CO_2 reduction across all plants would then require a minimum carbon price of 60 € $t_{CO_2}^{-1}$. Therefore large scale biomass deployment is not expected to happen with the current EU-ETS prices.

- **The differences in location and energy demand across the plants impact the economic viability of bioenergy not only on a country level, but also on a plant level.** For example, biomass deployment for a French plant in Dunkerque would start to become financially appealing at a carbon price of 20 € $t_{CO_2}^{-1}$, whereas the iron and steel plant at Fos-sur-Mer would require a minimal carbon price of 25 € $t_{CO_2}^{-1}$. This makes certain plants in the same country more willing towards bioenergy deployment than others, which might see opportunities in sufficient CO_2 reduction in other technologies. Hence bioenergy should not be treated as a "fit-for-all" solution, but rather as one of the technologies within the mix deployed across different plants in the near future.

- **Overall, France has been identified as the most promising country for bioenergy deployment within the European iron and steel industry.** Even though Romania presents the lowest bioenergy costs, France has a greater emission reduction potential in total. At the same time, France would be able to supply all the necessary biomass resources domestically and already demonstrates co-location of sufficiently strong steel industry and supportive policies, which would enable long-term viability of the solution.

- **Emission reduction potential of bioenergy could be significantly enhanced by its co-deployment with CCS.** Full-scale application of bio-CCS presents an opportunity for achieving emission savings as large as 100 %, however, bio-CCS option has not been discussed thoroughly for iron and steel so far. Research is hence necessary to explore further this topic and evaluate the feasibility of bio-CCS for European iron and steel industry from the technical perspective.

- **Bio-CCS deployment across the European integrated steel plants would require overcoming barriers related to bioenergy as well as CCS.** As barriers related to CCS are mainly of legal and public acceptance nature, they are currently harder to overcome than issues related to bioenergy deployment, mainly related to biomass availability. From the economic perspective of bio-CCS, the most viable plants are in Ijmuiden (Netherlands) and Liegè (Belgium). Those plants present the best opportunities to overcome barriers related to the CO_2 transport and storage, whilst also being able to source consistently the required amount of biomass, even though majority would be imported. Carbon-neutrality within the EU via bio-CCS would be of an average CO_2 avoidance cost of 80 € ${t_{CO_2}}^{-1}$. The resulting expenditure would make the European iron and steel products uncompetitive on the global market.

- **The biggest cost reduction potential of bio-CCS could be expected from the CO_2 capture aspect.** Technology learning should significantly decrease the CO_2 capture cost as the rate of CCS deployment will increase. Sharing CO_2 pipeline network by plants could also lead to cost reductions, however, the contribution of CO_2 transport to the total CO_2 avoidance cost using bio-CCS is already minor. The industry would require significant support from government to get the first bio-CCS plant in place, which would initiate further technology learning from the first bio-CCS deployment within this industry.

- **The EU presents a high suitability to deploy bioenergy across its integrated steel plants, however, better policy mechanisms are required to support such type of fuel-switching**. From the steel production cost perspective, the EU-ETS or carbon price are not the best mechanisms to enhance bioenergy deployment, as they could lead to a reduction of iron and steel production within the EU and carbon leakage. It is also important to note that neither bioenergy or CCS reduce the energy input and hence improve the energy efficiency of the production process. This should be a key concern that the European iron and steel industry should have, when selecting bioenergy over other existing or innovative technologies as a strategy to decarbonise this industry in the future.

6.2 Contributions to knowledge

The present work contributes to the existing knowledge principally in two ways. First, it enhances the understanding about the most strategic way to decarbonise the European iron and steel industry and second, it establishes a methodology that would enable policy makers to obtain such knowledge. Starting with the latter, the Global Suitability Index developed in this work is the first methodology of its kind that provides a global comparison of the best use of bioenergy for a specific application. The availability of this tool supports strategic utilisation of the limited biomass resources on a global scale. The developed index is a fundamental improvement in studying strategic utilisation of bioenergy, which so far has been done only by performing detailed studies requiring a significant investment of time and effort. It is important to point out that the purpose of the Global Suitability Index is not to substitute these studies. Instead, it should be undertaken as an initial step before such analyses are performed. This way, spending a large effort on detailed studies of unsuitable locations are avoided, whilst giving an opportunity to evaluate countries which would not be considered otherwise. In addition, this tool does not require any expert judgement, as the suitability thresholds are defined by the data. Therefore, it can be used by anyone, which is its key advantage. One can also see the benefit in reducing the extent of subjectivity in assessing the fitness for purpose, as nobody – potentially biased member – is setting those thresholds. Instead, it is all based on the distribution of the data. The fully defined methodology in Excel, with a step-by-step description, makes it easy for anyone to adapt and assess the bioenergy appropriateness also for other sectors.

Assessment methodologies often face problems of incomplete datasets. This is even further enhanced when dealing with global statistics, as some countries do not provide the specific data or the provided data have been purposely skewed. This work tackles this problem during the development of the *Global Suitability Index*. Using the NIPALS algorithm (please see Appendix A) and variable average, it is able to handle such partially fragmented data. This is a particularly useful contribution to knowledge as the defined approach could be applied in a wide range of applications, where it is dealt with a large set of incomplete data.

This work also enhances analysis of strategic biomass utilisation via an exclusively spatial-explicit approach. As far as the author is aware, the research on biomass sourcing for iron and steel has had only energy balance approach, where it evaluated the amount of nationally available resources versus the potential demand from the iron and steel. For the first time, this work has actually taken into consideration the exact locations of the biomass resources, the existing biomass demand and the iron and steel plants. In detail, the development of the iron and steel module within the existing techno-economic BeWhere model provides an insight into how and from where exactly the biomass would be sourced as well as how it would be transported. This is a very important insight for the iron and steel plant operators as well as policy makers to understand, whether the fuel switch would enhance the use of local resources or rather enhance its reliance on energy imports. The model development and the policy relevance has been awarded by the Peccei Award at IIASA, after series of nominations by IIASA's programme representatives and international peer-review process, which further demonstrates its importance.

In addition, the research related to the iron and steel module development has identified limitations in a series of previous studies. Specifically, some studies have added emission offset from biomass substitution for coking coal at coking plants together with emission offset resulting from substitution of biomass for coke charged at the top of the blast furnace. In the case of simultaneous deployment of both of those approaches, the top charge coke would already have some biomass content, which could not be offset again when substituted by bio-based fuel. This is an important limitation pointed out by this work, as those findings can lead to overestimating the maximum CO_2 reduction that could be achieved. This work also proposes a methodology, which resolves this issue by allowing only one of those options to happen. The detailed module description in the published articles then provides a platform for defining iron and steel modules for any future work on this topic.

Future studies will also benefit from the CCS module developed within the *BeWhere EU – iron & steel* model, which demonstrates how to define the CO_2 capture technologies and CO_2 transport network specifically for integrated steel plants. Particularly the developed framework that is able to estimate the CO_2 transport cost for a group of plants, which share the CO_2 pipeline network, is an important research for a wide range of other CCS studies. The development of CCS module also allows to study bio-CCS applications for the iron and steel. As the integrated steel plants offer opportunities only for partial substitution, the model has to be able to differentiate between zero, negative and avoided emissions. Their description in the model and correctly defining the final CO_2 intensity provides a fundamental knowledge about how to handle those for other studies of a similar nature.

This research also demonstrates the different opportunities for biomass substitution at a plant level, where previous work on this topic has done studies only on a country level. As far as the author is aware, there is not a specific study which would show differences in the CO_2 avoidance cost across each individual plant. The existence of such knowledge is very important for both, plant operators as well as policy makers, as it can explain various trends, such as, why certain policy mechanisms have not been as successful as predicted or why certain plants in the same country would be more willing towards biomass substitution than others. This work demonstrates the relationship between carbon price and emission reduction potential on a plant level, which is a useful finding for any future policy making aimed to decarbonise the iron and steel industry.

The vague understanding of the size of the biomass demand potentially coming from the iron and steel plants has been also addressed here. In addition, the work raised concerns related to biomass availability for other applications in the future as well as insufficient facilities for charcoal production that would be required. Those findings are very important as they divert the focus from commonly-discussed economic and biomass availability issues to the practical problems, such as lack of infrastructure and appropriate facilities. The provided discussion compares bioenergy with other strategies and points out a critical fact that even though biomass presents an opportunity to significantly decarbonise the industry, it does not lead towards the reduction of the energy intensity of the process. This points out a significant gap in the existing research, which should address the dilemma whether we should aim to achieve carbon-neutrality via increasing energy demand or reducing energy demand but achieving only partial decarbonisation.

Lastly, the work also enhanced knowledge on the barriers related to the CCS deployment. In general, the feasibility of CCS is often criticised and questioned due to the economic viability. This work raises an awareness of the non-economic barriers that the iron and steel plants are facing, which might be in the end the “deal-breakers”. Further elaboration of those beyond the current work is however necessary. The next section focuses on the limitations of this work and areas for its improvements.

6.3 Limitations and ideas for future work

The work presents multiple areas for improvements, which could be addressed in the future work. This section focuses on three main aspects related to challenging carbon neutrality of biomass, performing sensitivity analysis of the results and comparing bioenergy with other low carbon technologies.

6.3.1 Emissions accounting off-site as well as on-site

Carbon neutrality of the bio-based fuels is one of the commonly used assumptions when studying bioenergy systems. In reality, the produced biomass could be far away from being carbon neutral as the emissions resulting from biomass transport, harvesting and land use change could significantly impact the net carbon balance of the fuel. Therefore, one of the key limitations of this work is its focus only on emissions occurring on-site of the iron and steel plants. The present study would be greatly enhanced if the work also considers the off-site emissions. The findings would then provide an insight into whether such fuel switching is good from the whole system perspective too. However, understanding a full environmental impact of biomass utilisation would ideally require a detailed Life Cycle Assessment, which performing for each plant would be highly time and money consuming (even with the assistance of the BeWhere model). A potential solution would be choosing only one or two specific plants. The corresponding findings, even if they would be only for one specific integrated steel plant, would be very beneficial to enhance the understanding of the real environmental benefit that such fuel switching achieves. The findings would then be able to confirm or disprove whether the fuel switching to biomass is an environmentally strategic solution from the whole system perspective, not only a plant perspective.

6.3.2 Relationship between non-economic barriers/opportunities and the economic attractiveness

A major part of the present study focused on the economic feasibility of the solution, but the non-economic barriers have been only briefly mentioned. This a large area for an improvement as overcoming non-economic barriers could significantly increase the economic viability of any project. Performing a local sensitivity analysis, that would provide insight into how much each non-economic barrier related to the bioenegy/bio-CCS deployment would impact its economic viability, would greatly enhance the findings of the project. Also, the work has identified that most of the biomass would be sourced domestically/from within the EU. Therefore, it would be interesting to quantify the economic impact of its local sourcing on the local economies. In detail, local biomass sourcing presents a great opportunity for new employment opportunities and enhancement of regional production. In addition, producing fuel within the EU, instead of importing it, creates additional benefit in terms of energy security. Transferring all those opportunities and reflecting them in the final costs would provide an important insight into how much each government should financially support such transition to maximise the returns.

6.3.3 Vision for 2050

The present work has assessed bioenergy as an emission reduction strategy, but lacks its detailed comparison with other low carbon technologies, which are also promising high level of decarbonisation for the iron and steel sector. The current analysis would be greatly enhanced by performing a comparative study, which would not only optimise the biomass resources, but also other technology alternatives. This would increase the robustness of the conclusions achieved in the present work on which plants/countries should deploy bioenergy within their iron and steel making industry. At the same time, commercialisation of those technologies will take few years due to their current technology readiness level as well as time required to obtain all the planning permissions. Therefore, including the time-perspective in such analysis (up to, e.g., 2050) would greatly enhance the understanding of the importance of each technology and the role of bioenergy in-between them.

Due to the data availability and confidentiality, this work assumes that the plants vary only in the amount of their annual steel output. Otherwise, it is considered that each plant has the same set-up. In reality, all plants are significantly different in terms of their units as well as the amount and type of energy they use. Obtaining plant specific data would enhance the quality of the future research and provide a better comparison of the opportunities for biomass utilisation.

Appendix A

Data analysis for the steel production factor

Steel production within the 40 studied countries is influenced by multiple factors. To select the key variables to be used within the GSI in Chapter 5 for the steel production factor, this work uses Principal Component Analysis (PCA). The PCA is a multivariate data analysis tool commonly used, for example, in the field of chemometrics, which studies chemical data [232]. The method is purposely selected for the present work as it is able to examine patterns between the studied data, beyond correlation values. This is done by data transformation into a new set of orthogonal axes, called principal components (PCs) and studying the loadings values obtained for each variable. The most influential variables in regards to the amount of steel produced in a country via BF-BOF route are identified from 18 potential variables. Due to the incomplete dataset, nonlinear iterative partial least squares (NIPALS) algorithm is used instead of the conventional PCA. The advantage of NIPALS over PCA is that it can numerically calculate the PCs without the need of the covariance matrix by using so-called peeling procedure, where eigenvectors are iteratively calculated and then peeled off from the dataset [231].

The data analysis is performed using mathematical software R, 64-bit version, using `nipals` function under `plsdepot` library. The number of PCs is chosen based on the change in slope in the scree plot showing the percentage variation represented by each PC [34, 46, 232]. As there is a significant reduction in the variation that PCs represent for the fourth PC onwards, the present study considers only the first three PCs (of cumulative percentage 66.1 %) for further analysis.

The relationship between the variables is observed from plotting loadings values of each PC against each other, specifically focusing on each variable's distance from the

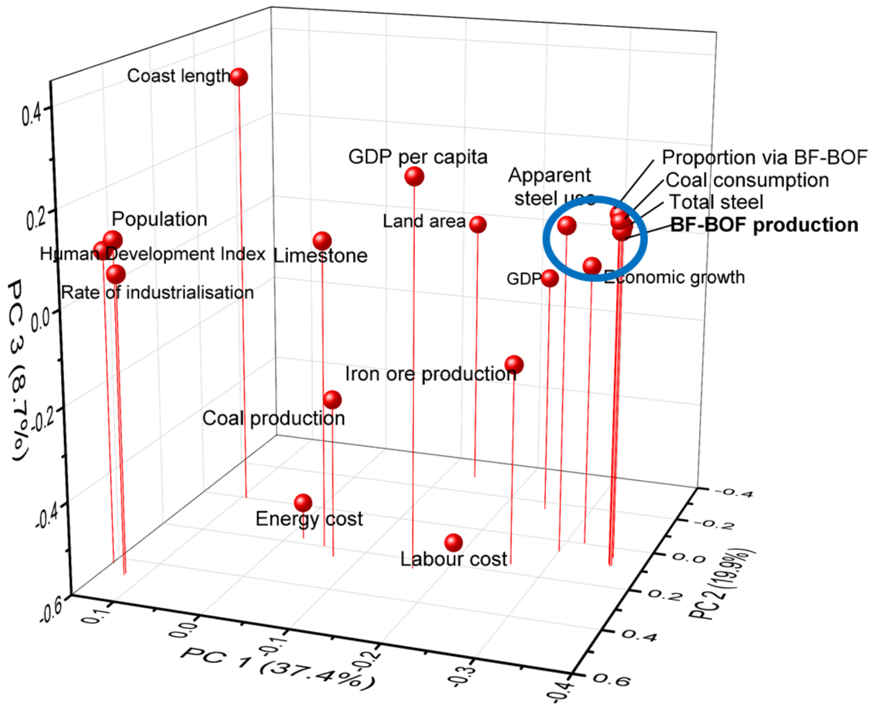


Figure A.1: 3D plot of the scores for the first three principal components, representing in total 66.1 % of total variation in the data. Strongly correlated variables are grouped closely together. This indicates economic growth, apparent steel use, coking coal consumption, proportion of steel produced via BF-BOF route and total steel production are all variables important for steel production via BF-BOF route. Figure taken directly from [138].

origin and the angle it forms with other variables. To improve visualisation, the loadings of each variable are plotted in a 3-D plot in Figure A.1. Based on the position of the variables around the BF-BOF production variable, the present work identifies:

- Total steel
- Coal consumption
- Apparent steel use
- Proportion of steel produced via BF-BOF route
- Economic growth

as the key variables for the steel production factor and considers those in the further analysis in Section 5.3.2. Further details, including the full dataset used for this study, can be found in Mandova *et al.* [138], specifically the Appendix and Supplementary materials accompanying the publication.

Appendix B

Conversion tables

Table B.1: Conversion factors commonly used for wood biomass resources [142].

From/to	Mm^3	Modt	PJ	Mtoe
Mm^3	1	0.50	8.72	0.21
Modt	2.00	1	18.18	0.44
PJ	0.11	0.055	1	0.024
Mtoe	4.76	2.26	41.87	1

Table B.2: Equivalence across different steel products. Based on values given in [106].

... generates ...	t of HM	t of CS	t of HRC
1 t of hot metal (HM)	1	1.1158	1.0271
1 t of crude steel (CS)	0.8963	1	0.9206
1 t of hot rolled coil (HRC)	0.9736	1.0863	1

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