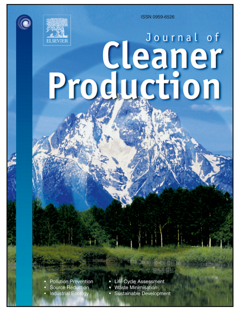
Accepted Manuscript



Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage

Hana Mandova, Piera Patrizio, Sylvain Leduc, Jan Kjärstad, Chuan Wang, Elisabeth Wetterlund, Florian Kraxner, William Gale

PII: S0959-6526(19)30272-0

DOI: https://doi.org/10.1016/j.jclepro.2019.01.247

Reference: JCLP 15634

To appear in: *Journal of Cleaner Production*

Received Date: 20 October 2018

Revised Date: 17 January 2019

Accepted Date: 22 January 2019

Word count: 7317 (all text in this document, except references)

Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage

Hana MANDOVA[1,2]*, Piera PATRIZIO[2], Sylvain LEDUC[2], Jan KJÄRSTAD[3], Chuan WANG[4,5], Elisabeth WETTERLUND[2,6], Florian KRAXNER[2], William GALE[1]

[1] University of Leeds, Leeds, United Kingdom

[2] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

[3] Chalmers University of Technology, Gothenburg, Sweden

[4] SWERIM, Luleå, Sweden

[5] Åbo Akademi University, Biskopsgatan 8, FI-20500, Åbo, Finland

[6] Energy Engineering, Division of Energy Science, Luleå University of Technology, Sweden

**Corresponding author: pmhm@leeds.ac.uk*

Abstract

The 30 integrated steel plants operating in the European Union (EU) are among the largest single-point CO_2 emitters in the region. The deployment of bioenergy with carbon capture and storage (bio-CCS) could significantly reduce their fossil-based CO_2 emissions. In detail, the results demonstrate that CO_2 emission reduction targets of up to 20% can be met entirely by biomass deployment. A slow CCS technology introduction on top of biomass deployment is expected as the requirement for emission reduction exceeds 20%. Bio-CCS could then be a key technology, particularly in terms of meeting targets above 50%, of CO_2 avoidance cost ranging between €60 and €100 $t_{CO_2}^{-1}$ at full-scale deployment. The future of bio-CCS and its utilisation on a larger scale would therefore only be viable if such CO_2 avoidance cost were to become economically appealing. Small and medium plants in particular, would economically benefit from sharing CO_2 pipeline networks. CO_2 transport, however, makes a relatively small contribution to the total CO_2 avoidance cost. In the future, the role of bio-CCS in the European iron and steelmaking industry will also be influenced by non-economic conditions, such as regulations, public acceptance, realistic CO_2 storage capacity, and the progress of other mitigation technologies.

Keywords:

BECCS; bio-CCS; blast furnace; industry; charcoal; CCS

Highlights:

- Bio-CCS can help iron and steel making become close to carbon neutral.
- Average bio-CCS avoidance cost in the EU is about €80 $t_{CO_2}^{-1}$.
- Netherlands, France, and Belgium have the lowest bio-CCS deployment cost.

1 Introduction

The European iron and steel industry annually generates over 200 million tons of carbon dioxide (Mt_{CO_2}) (Borkent and Beer, 2016), which amounts to 5% of all CO_2 emissions produced across EU-28 countries in 2016 (Eurostat, 2016). The majority of these emissions come from the 30 integrated steel plants that produce 60% of the European steel output (World Steel Association, 2017). Their high emission intensity is due to the nature of the iron and steel production process from iron ore, which in comparison to scrap recycling, is two and half times more emission intensive (Beer et al., 2000). As the steel scrap recycling rate is not sufficient to meet the increasing demand for steel, ore based steel production via a blast furnace-basic oxygen furnace (BF-BOF) route is expected to remain dominant until at least 2050 (Pauliuk et al., 2013). Therefore, to achieve the EU emission reduction targets for 2020, 2030 and 2050 (European Commission, 2017), the 30 integrated plants will have to implement breakthrough technologies for CO_2 emission abatement (European Commission, 2013). A key technology that can contribute significantly to deep emission cuts is carbon capture and storage (CCS) (European Commission, 2011a, 2011b; ZEP, 2013). A hybrid approach that combines CCS with biomass (bio-CCS) could provide even further emission reductions in this industry (Arasto et al., 2014). The average 2017 price of European emission allowances of €5.80 $t_{CO_2}^{-1}$ (Business Insider, 2018) and an absence of bio-CCS specific incentives, make its application in Europe unrealistic for the moment (EUROFER, 2013). However, the likely overshoot of the remaining CO_2 budget for limiting global warming to below 2°C (UNEP, 2017), in combination with the hitherto slow transition to low-carbon iron and steel making technologies, is increasing the need for the deployment of significant CO_2 emission reduction measures like bio-CCS in Europe in the near future (Mintenig et al., 2017; Scott and Geden, 2018).

Broadly speaking, the key role of negative emission technologies is to generate negative emissions that would compensate for CO_2 emissions from sectors that may have a hard time reaching carbon-neutrality (such as agriculture, aviation or industry) (Erbach, 2015). Specifically, bio-CCS offers a way to generate energy that is carbon neutral/negative, which makes it suitable for co-application during energy conversion or with energy intensive industrial processes. Scenarios for the decarbonisation of the iron and steel industry generally involve CCS, either on its own (Pardo and Moya, 2013; Solano Rodriguez et al., 2017), or in combination with a top gas recycling blast furnace process (EUROFER, 2013; Remus et al., 2013). Due to the technical role that fossil fuels play in the iron ore reduction process, only a limited biomass substitution is feasible (Mousa et al., 2016; Suopajärvi et al., 2017). Therefore, additional measures such as bio-CCS deployment would be needed to achieve high levels of CO_2 reduction across an integrated steel plant. The introduction of bioenergy with CCS could theoretically achieve carbon-neutral steelmaking (considering that bioenergy can substitute over 40% of fossil-based CO_2 emissions (Mandova et al., 2018) and that CCS can capture over 60% of the CO_2 emissions that occur on-site (IEAGHG, 2013)) without a significant retrofit of a steel plant. However, this carbon-neutral iron and steelmaking opportunity is currently being impeded by the challenges raised by any deployment of bio-CCS.

Deployment of bio-CCS has so far been stagnant, with only a few small demonstration-scale bio-CCS projects currently being operational (e.g., the Illinois Industrial CCS Project) (Global CCS Institute, 2018). Any bio-CCS application within fully fossil fuel-based processes would necessitate simultaneously overcoming barriers to both bioenergy and CCS implementation. Issues related to the actual implementation and cost of CO_2 capture, transport and storage, uncertainties in the long term response of the environment to CO_2 storage, and public acceptance or ability to prolong reliance on fossil fuels, are the main arguments limiting CCS progress (Fuss et al., 2014). As of 2018, there are only 30 Mt_{CO_2} stored annually worldwide (Global CCS Institute, 2018). CCS deployment will therefore have a hard time reaching the annual CO_2 storage volumes required by, for instance, the International Energy Agency (IEA) 2°C scenario of 400 Mt_{CO_2} by 2025 (IEA, 2014). Insufficient policy support to create a business case for CCS, for example, in the EU Emission Trading System (ETS) (Purvis and Vaghi, 2015), makes the required CCS expansion unrealistic over the next decade. On the same note, sustainable biomass supply constraints, concerns associated with competition between bioenergy and food production, the complexity of emission accounting, as well as direct and indirect land use change, are major arguments against increased bioenergy use (Sanchez and Kammen, 2016).

There is currently no commercialised application of bio-CCS in the iron and steel industry, even though bioenergy and CCS indepently, are commercialised (e.g., charcoal utilisation in Brazilian mini blast furnaces (Machado et al., 2010) and a CCS facility in Abu Dhabi with an annual capture capacity of 0.8 Mt_{CO_2} (Global CCS Institute, 2018; IEA, 2014)). The suitability of bio-CCS is highly dependent on geographic location, which diversifies opportunities for large-scale bio-CCS application across steel plants. Factors such as industrial plant structure, the availability of CO_2 storage and transport options, sufficient sustainable biomass resources, supportive regulatory frameworks, etc. (Gough and Upham, 2011), differ for individual plants across different countries and regions. There is currently no comparison of bio-CCS opportunities for individual integrated steel plants, or evaluations of bio-CCS as a strategy for carbon-neutral iron and steelmaking available for the iron and steel industry in Europe. A few studies previously focused on either bioenergy or CCS for iron and steel production in Europe, but to our knowledge, no other studies have considered combining the two technologies. Specifically, both Mandova et al. (2018) and Suopajärvi and Fabritius (2013) conclude that biomass deployment in European iron and steelmaking is limited by economic feasibility rather than biomass availability. The CCS studies by Birat (2010) and Remus et al. (2013) on the other hand, point out a lack of sufficient experience with this technology. All of these studies, however, show that neither bioenergy nor CCS would achieve a 100% emission reduction in the iron and steel sector on their own. Therefore, research on combining both technologies as bio-CCS is important in order to understand their compatibility, particularly if iron and steel industry aims to achieve carbon neutrality. Such research is also significant to understand the role of other low carbon steelmaking processes that are currently under development, including the use of blast furnaces with top gas recycling (van der Stel et al., 2013), the HIsarna process (Meijer et al., 2011) or hydrogen based steel making (HYBRIT, 2017; Ranzani da Costa et al., 2013).

The objective of this work is to evaluate bio-CCS as a strategy for achieving carbon-neutrality across European iron and steel plants that produce steel via the BF-BOF route. Using the techno-economic *BeWhere-EU model*, the work (1) identifies the importance of bio-CCS within the technology mix when meeting different emission reduction targets, (2) estimates the CO_2 avoidance cost of the bio-CCS deployment, and (3) discusses the potential reduction in CO_2 transport costs by large scale integrated CO_2 pipeline networks. This study bridges the gap in the literature on bio-CCS opportunities in the iron and steel industry and increases the general knowledge on bio-CCS deployment costs in Europe. The outcomes also provide an opportunity to identify potential CO_2 clusters across integrated steel plants, as well as knowledge about possibly integrated CO_2 transport networks.

2 Methodology

2.1 Modelling approach

Studying the potential of bio-CCS within a large system requires a modelling approach that accounts for the biomass supply chain, the considered industry, and the CCS network. The approach also has to be able to study the interaction between the three systems across the studied time frame, and take into account the spatial distribution of elements as well as the technical limitations that occur when they are applied within the same system. In our previous work using the *BeWhere-EU* model (IIASA, 2015), we already linked biomass and iron and steel plants in this way (Mandova et al., 2018). This work extends the *BeWhere-EU iron & steel* model by adding a CCS framework for iron and steel, including CCS linkage to biomass, which provides an opportunity to simultaneously study both the CCS and bio-CCS systems. The section below gives a brief overview of the model, with further information provided in the supplementary material.

The *BeWhere-EU iron and steel* model is written in the General Algebraic Modelling System (GAMS), using Mixed Integer Linear Programming (MILP) and CPLEX as solver. The concept of the model is to split the studied geographic region (EU-28) into equally sized grid-cells, each covering an area of 40 km × 40 km. Each grid-cell then contains area-specific information that is important for modelling the system, including:

- types, amounts and costs of available feedstock;
- existing biomass demand;
- distance, mode of transport and biomass transport costs between different grid-cells;
- annual CO_2 emissions and energy demand of integrated steel plants;
- CO_2 storage potential, as well as CO_2 capture, transport and storage costs.

The cost of biomass upgrading, the types of fossil fuels used in an integrated steel plant, and different CO_2 transport network possibilities are also included in the model. Figure 1 illustrates all aspects considered in this work. Based on this information, the model minimises the total cost of the system on an annual basis. The total system cost includes the cost of the biomass supply chain, fuel used in iron and steel plants, as well as all expenditure related to the deployment of CCS. The opportunities for bio-CCS implementations across different plants are then studied by introducing a range of CO_2 emission reduction targets as one of the constraints.

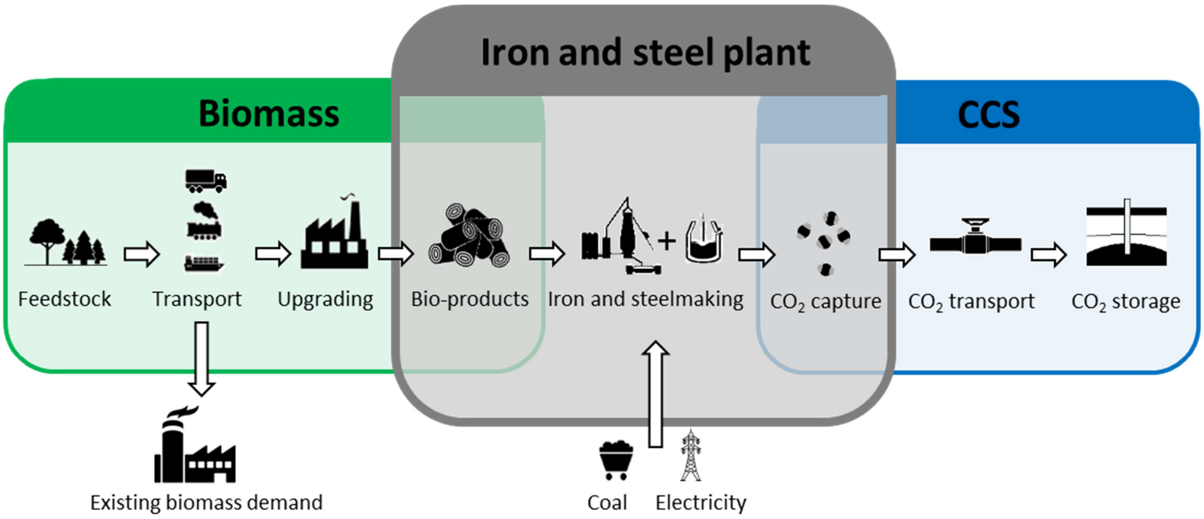


Figure 1: Aspects considered within the bio-CCS supply chain in this study.

As shown in Figure 2, the complexity of the modelled system requires the inclusion of a variety of input data, constraints and internal data calculations. Specifically, the model is composed of three modules, where the core module *BeWhere-EU iron & steel* is using the outputs of the biomass module (labelled *BeWhere-EU*) and the CCS module (labelled *CO_2 TranStorage*). In particular, the biomass module is used to subtract the biomass requirement of the existing industries from the total biomass potential. The CCS module has been developed to obtain different CCS infrastructure configurations connecting the plants to potential CO_2 storage sites using a minimum spanning tree algorithm (Hillier, 2012). The core – iron and steel – module connects the two modules and provides outputs specific to the iron and steel industry study. A mathematical description of each module can be found in the supplementary material. Table 1 presents a summary of input data values specifically for costs and the following sections give further details on the calculations performed.

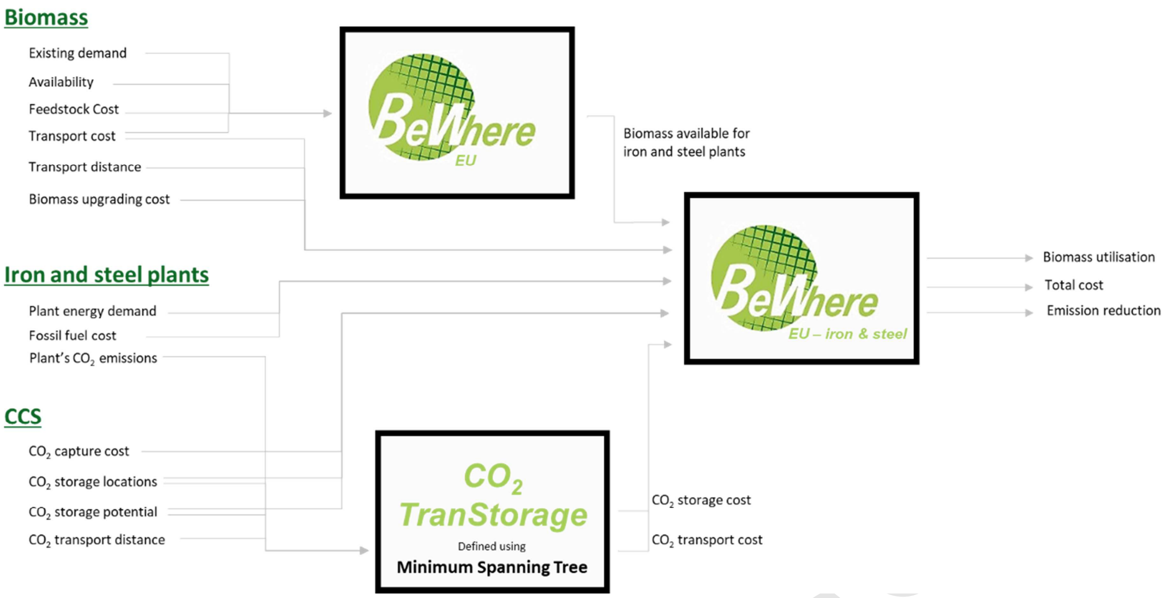


Figure 2: Summary of inputs and outputs considered for this study. Values used for each input parameter is provided in the supplementary material.

2.2 Biomass supply chain

The biomass supply chain considers feedstock supply, transport and upgrading. The total theoretical biomass potential within the EU in 2020 is estimated to be 8.5 EJ year^{-1}. This potential includes stumps, stemwood and logging residues of coniferous and non-coniferous trees, with costs ranging from €0.20 up to €8.30 GJ^{-1} (with price depending on the type of wood and country of origin) (Dees et al., 2017). To incorporate biomass sustainability aspects in the modelling, only 70% of the theoretical potential is considered. The model allows inter-European biomass trade, as well as biomass imports from non-EU countries to specific harbour locations. The imported biomass from non-EU countries is assigned a cost 20% higher than the average biomass cost in the country where a specific harbour is located, in order to account for additional expenditure due to import taxes and long-distance transport. Biomass harvested outside the EU is generally imported already pre-processed, for example, in the form of pellets. However, as the current work assumes that biomass upgrading to the final product is done on-site of the iron and steel plant, the modelling approach required raw biomass import from outside of the EU. The cost of biomass imports from outside the EU ranges from €3.56 to €6.01 GJ^{-1} (exact values are available in the supplementary material). Transport of biomass from supply points to demand points is considered by truck, train and ship, with the specific cost of each biomass type approximated on energy basis. Form of transport and the corresponding distances are obtained from spatial data using the network analysis tool in the ArcGIS software. The studied biomass demand includes the pulp and paper industry (total of 1.4 EJ year^{-1}) (CEPI, 2017), sawmills (1.6 EJ year^{-1}) (FAO, 2016) and heat and power plants (1.0 EJ year^{-1}) (Platts, 2017). In total, 2.0 EJ year^{-1} of available biomass potentially suitable for iron and steel production is identified from the biomass module (*BeWhere-EU*) after meeting the existing demand. The distribution of the available biomass in relation to the 30 integrated steel plants is shown in Figure 3.

Table 1: Summary of cost input values considered for this study. Further details are given in the supplementary material.

	Input value	Citation	Note
Biomass feedstock			
Domestic coniferous trees	€0.0 – €6.9 GJ^{-1}	(Dees et al., 2017)	Spatially explicit prices
Domestic non-coniferous trees	€0.1 – €8.3 GJ^{-1}	(Dees et al., 2017)	Spatially explicit prices
Non-EU feedstock	€3.6 – €6.0 GJ^{-1}		Value 20% higher than average biomass cost in the country of the importing harbour.
Biomass transport			
Lorry	~€0.00255 GJ^{-1} km^{-1}		Average values dependent on the distance travelled, as defined in a work by Börjesson and Gustavsson (1996), and fuel cost in the country. Further details are provided in the supplementary material.
Train	~€0.00299 GJ^{-1} km^{-1}		
Freight	~€0.00210 GJ^{-1} km^{-1}		
Biomass upgrading			
Pelletisation	€1.03 – €2.98 GJ^{-1}	(Uslu et al., 2008)	Country specific values defined using purchasing power parities (European Commission, 2016).
Torrefaction	€1.28 – €3.72 GJ^{-1}	(Uslu et al., 2008)	
Slow pyrolysis	€1.15 – €3.34 GJ^{-1}	(Norgate et al., 2012)	
Fossil fuel cost			
Coking coal	€3.98 GJ^{-1}	(IEAGHG, 2013)	2017 values obtained using a 2010-2017 inflation rate.
Coke	€5.35 GJ^{-1}	(IEAGHG, 2013)	
PCI	€3.17 GJ^{-1}	(IEAGHG, 2013)	
Coke breeze	€5.35 GJ^{-1}	(IEAGHG, 2013)	
CO_2 capture cost			
CASE 1:	€54.4 – €93.4 $t_{CO_2}^{-1}$	(IEAGHG, 2013)	2017 values obtained using a 2010-2017 inflation rate. Country specific values obtained based on the national 2017 non-household electricity prices (Eurostat, 2017). Further details on calculations performed are given in the supplementary material.
CASE 2:	€53.1 – €96.5 $t_{CO_2}^{-1}$	(IEAGHG, 2013)	
CO_2 transport cost:			
Individual network	€0.523 – €36.7 $t_{CO_2}^{-1}$	(IEAGHG, 2005)	2017 values obtained using a 2005-2017 inflation factor. Further details are provided in the supplementary material.
Collaborative network	€0.191 – €63.3 $t_{CO_2}^{-1}$	(IEAGHG, 2005)	
CO_2 storage			
Saline aquifers	€15.8 $t_{CO_2}^{-1}$	(ZEP, 2011)	2017 values obtained using a 2010-2017 inflation rate.
Depleted oil and gas fields	€10.8 $t_{CO_2}^{-1}$	(ZEP, 2011)	

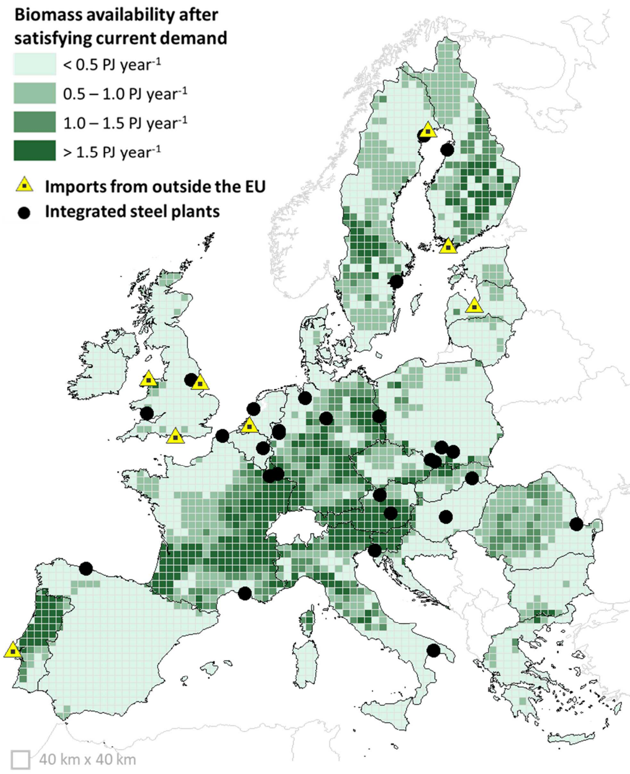


Figure 3: Location-specific biomass availability (locally sourced) after the demand from existing bio-based industries has been met. Seven trade points for biomass supply from outside of the EU-28 countries were considered.

Upgrading of any biomass to bio-products: wood pellets, torrefied fuel and charcoal, is assumed to take place on-site at iron and steel plants, at production costs of €2.15 GJ^{-1} for wood pellets (Uslu et al., 2008), €2.68 GJ^{-1} for torrefied fuel (Uslu et al., 2008) and €2.41 GJ^{-1} for charcoal (Norgate et al., 2012). The production costs (both converted and original values as presented in the supplementary material) have been scaled up or down using purchasing power parity (European Commission, 2016). CO_2 emissions related to biomass harvesting, upgrading and transport are not included, as the study considers only direct emissions based on steel production.

2.3 Technologies for CO_2 emission reduction in integrated steel plants

In total, 30 integrated steel plants – the full number of currently operating plants using BF-BOF across EU-28 countries – are considered. In order to maintain transparency under limited data availability and confidentiality, this work assumes that each plant has the same technology and structure as a typical West European plant, as described in the IEA Greenhouse Gas (GHG) report (IEAGHG, 2013). The energy demand of each plant is estimated from the plants' annual hot rolled coil (HRC) production. This is obtained from each plant's data on hot metal production in 2016 (VDEh data exchange, 2017), which is then further calibrated so that country specific crude steel production corresponds to data published by the World Steel Association for the same year (World Steel Association, 2017). In addition, it is assumed 1 t of hot metal produces 1.113 t of crude steel and 1.027 of hot rolled coil, as presented in the IEAGHG report (IEAGHG, 2013).

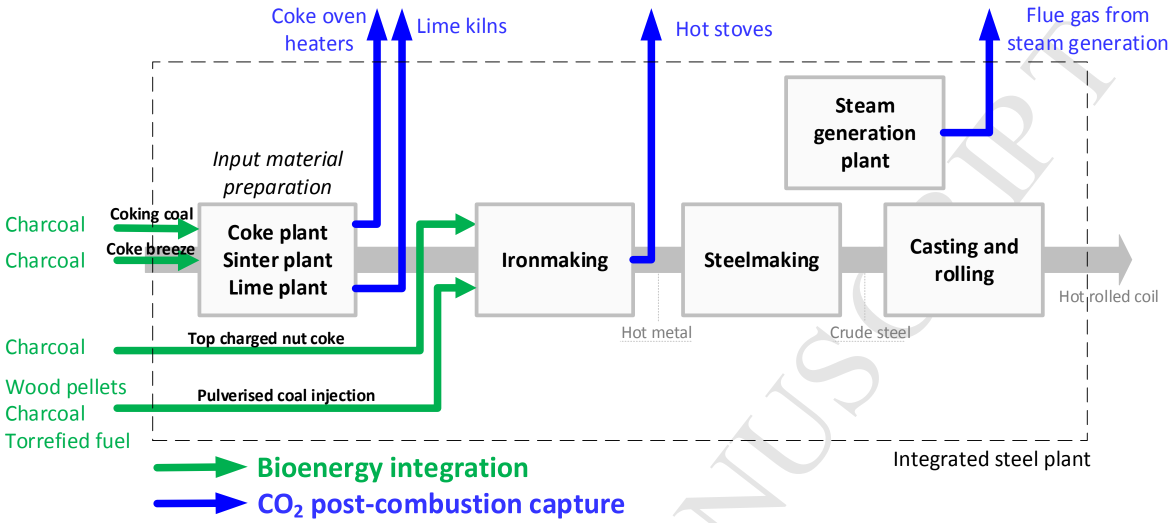


Figure 4: Possibilities for bioenergy integration and post-combustion CO_2 capture in an integrated steel plant.

Substitution of fossil fuels by biomass is considered on an energy basis. Figure 4 demonstrates the bioenergy integration possibilities in a typical integrated steel plant for different coal-based fuels. It is important to note, that due to differences between fossil fuels and bio-products in terms of mechanical strength, reactivity, chemical composition, heating value, etc., only partial substitution opportunities are provided (Fick et al., 2014). Table 7 in the supplementary material provides further details on the maximum substitution possibilities of each coal-based fuel by the specific bio-product considered in this work. In the *BeWhere-EU iron & steel* module then, bioenergy is first integrated into the iron and steel plants based on the supply cost in comparison to that of conventional fossil fuels. Generally, the bio-products are not economically competitive with fossil fuel prices (ranging from €3.52 to €5.94 GJ^{-1} (IEAGHG, 2013)) and so, no fossil fuel substitution is experienced in the model. Therefore, the bio-products are also introduced based on the amount of emissions they could potentially offset, in order to meet the imposed emission reduction targets, while keeping a record of the additional costs incurred by each individual integrated steel plant. These aspects are at the core of the *BeWhere-EU iron & steel* module and follow the model development process presented in our previous work (Mandova et al., 2018).

The integration of CCS in iron and steel plants is considered in terms of the deployment of post-combustion capture, which can eliminate emissions from existing plants without significant retrofit. The shorter shut-down time and lower capital investment in comparison to other CO_2 capturing technologies (e.g., pre-combustion capture, oxy-fuel combustion capture or capture from industrial process streams (IPCC, 2005)) makes it a more likely near-term capture option. This work uses the specifications of the CO_2 post-combustion capture technology that incorporates standard monoethanolamine (MEA) solvent for iron and steel plants, as described in the IEAGHG report (IEAGHG, 2013). As per the report, two cases of CO_2 capture possibilities are considered:

- Case 1: CO_2 is captured only from flue gases from the hot stoves and steam generation plant. The net emission intensity of the final steel product (set to 2.09 t_{CO_2} t_{HRC}^{-1}) can be reduced by a maximum of 50% (to 1.04 t_{CO_2} t_{HRC}^{-1}) (IEAGHG, 2013).
- Case 2: On top of capturing all CO_2 from the units listed in Case 1, additional CO_2 is captured from flue gases coming from the coke ovens and lime kilns. The maximum CO_2 avoidance potential would increase to 60% (resulting in an emission intensity of 0.828 t_{CO_2} t_{HRC}^{-1}) (IEAGHG, 2013).

Because of multiple CO_2 sources across the plant, CO_2 capture across an integrated steel plant is more challenging than, for example, from a power plant. Therefore, despite assuming a 90% capture rate for all of the CO_2 absorbers, the other – uncaptured – sources of CO_2 emissions across the integrated steel plant and the increased CO_2 emissions attributed to the extra energy demand from the CO_2 capture installation, results in a net emission reduction of maximum 60%. The estimated CO_2 capture cost for each plant in 2017 includes the expenditure related to retrofitting the plant and extra energy use. The cost varies across the plants based on national electricity prices for the industry (Eurostat, 2017). In general, the average CO_2 capture costs applied are €64.50 $t_{CO_2}^{-1}$ and €70.40 $t_{CO_2}^{-1}$ for the first and second capture case, respectively. The calculations performed can be found in the supplementary material. Integration of the different options for post-combustion CO_2 capture within integrated steel plants is illustrated in Figure 4. As CCS avoids the release of CO_2 into the atmosphere, this work assumes zero emission intensity of captured fossil-based CO_2, and a negative emission value for captured bio-based CO_2.

2.4 CO_2 transport and storage

In terms of considering the transportation of large amounts of CO_2 and probable public opposition to onshore CO_2 storage (Margriet Kuijper, 2011), this work focuses only on CO_2 transport using pipelines for CO_2 deposition in offshore storage locations. In the CCS module

(*CO_2 TranStorage*) the shortest pipeline network that connects all CO_2 sources with storage locations, is defined. The connections are established by adapting an existing minimum spanning tree algorithm (GAMS, n.d.), the idea of which is to connect all vertices without any cycle, while minimising the total weight of all its edges (Hillier, 2012). To account for obstacles related to the pipeline routing, an extra 10% and 20% are added to the distance (measured as a straight line in ArcGIS) for offshore and onshore pipelines, respectively.

The cost of building the pipelines and the final CO_2 transport cost for each plant are calculated using the IEAGHG CO_2 transport cost curves (IEAGHG, 2005), scaled by the 2005 to 2017 inflation factor of 1.2 (Official Data Foundation, 2018). A concurrent development of the proposed CO_2 pipeline network is assumed, which is why the extra expenditure resulting from gradual CO_2 network development that would likely evolve in practice, is not considered. In addition, the network focuses only on connecting the 30 integrated steel plants, excluding possibilities for network connection with other plants (such as power, heat, cement, chemicals, etc.) and the corresponding possibilities for further cost reductions due to economies of scale.

The key factors influencing the cost are the pipeline length and the specific CO_2 flow. The CO_2 transport cost estimates also include the cost of compression up to supercritical pressure (above 73.8 bar), investment, operational and maintenance costs, as well as whether it is an onshore or offshore pipeline (IEAGHG, 2005). In addition, the calculation also takes into account the extra CO_2 flow as a result of increasing the amount of CO_2 produced at a plant due to the installation of CCS technology. A further description of the CO_2 pipeline cost calculations can be found in the supplementary material.

As mentioned above, only offshore CO_2 storage in saline aquifers or depleted oil and gas fields is considered, with locations around Europe shown in Figure 5. The storage/injection capacities are obtained from the Chalmers CO_2 storage database (Kjärstad and Johnsson, 2007). The storage and injection capacities, particularly in aquifers, are highly uncertain. The values listed in the Chalmers CO_2 storage database should therefore be considered as rough preliminary estimates. The cost of CO_2 storage is set to €10.80 $t_{CO_2}^{-1}$ for depleted oil and gas fields and €15.60 $t_{CO_2}^{-1}$ for saline aquifers (ZEP, 2011) (scaled by an inflation factor of 1.09 for 2010 to 2017 (Official Data Foundation, 2018)).

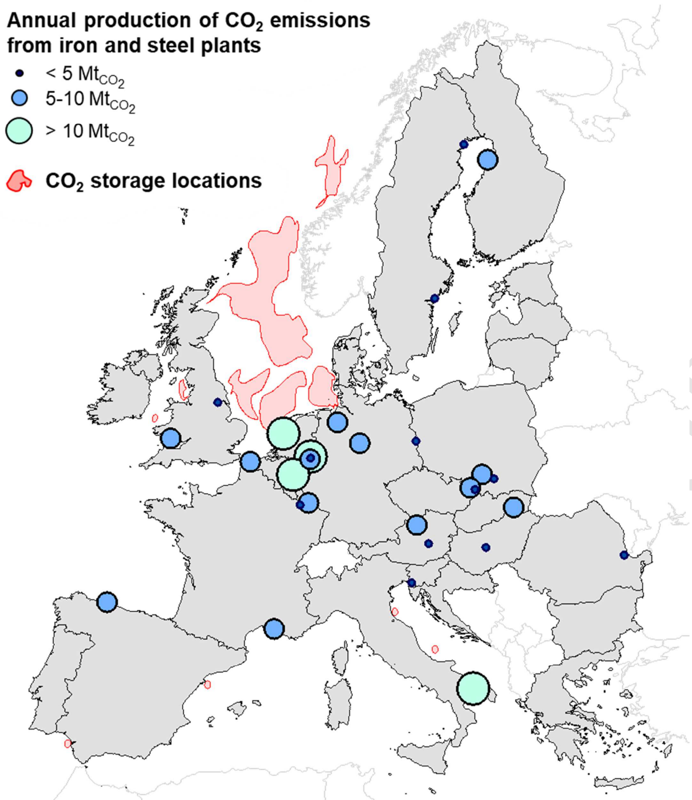


Figure 5: Locations of CO_2 sources and offshore storage locations relative to the location of integrated steel plants. Data on storage locations taken from Chalmers CO_2 storage database (Kjärstad and Johnsson, 2007).

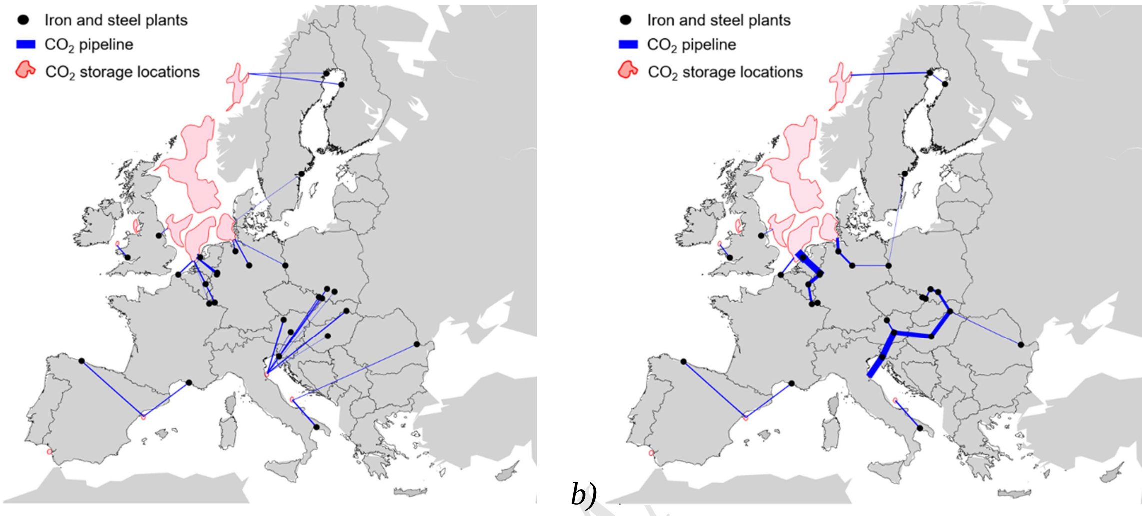
2.5 Scenario setting

To help answer our questions, we explore a range of scenarios that vary across two dimensions: (1) the CO_2 emission reduction goal to be achieved, and (2) the configuration of the physical CO_2 infrastructure.

To study the increasing importance of bio-CCS in the technology mix, we impose European emission reduction targets ranging from 0 up to 100%, with a 5% step level. The analysis focuses only on the CO_2 emissions occurring on-site for the integrated steel plants, in other words, it does not consider the produced emissions during fuel transportation, upgrading or production as such a study would require a detailed Life Cycle Analysis (LCA). The follow up discussion takes place on both plant and country level, in order to evaluate whether any country has an outstanding opportunity for bio-CCS deployment that would be able to significantly reduce CO_2 emissions on its own.

To account for the possibility of several plants sharing a CO_2 pipeline system, two CO_2 networks, classified as individual or collaborative, are considered (Figure 6). In both cases, the costs are calculated for a "plateau flow" of CO_2 (a CO_2 pipeline network where all plants start delivering their maximum CO_2 volumes from day one). It is important to note that achieving the proposed collaborative network would be difficult in practice since it is unlikely that all plants will deploy CCS/bio-CCS at the same time.

A number of non-economic barriers that can potentially influence CO_2 pipeline construction can be identified. This includes, for example, the 1996 London Protocol prohibiting the export of CO_2 for storage (International Maritime Organization, 2006), expected local opposition (Margriet Kuijper, 2011) or previous studies disclosing certain pipeline networks.



a) *b)*

Figure 6: Notional a) individual vs. b) collaborative CO_2 pipeline network based on minimum distance criteria and capacities of the CO_2 storage reservoirs.

3 Results

3.1 The importance of bio-CCS for various CO_2 reduction targets

The optimal technology mix to meet different CO_2 emission reduction targets is shown in Figure 7. After considering the three technologies – biomass, CCS, and bio-CCS – it emerged that the application of bio-CCS is required across all plants to achieve a 100% CO_2 reduction (of 189 Mt_{CO_2} $year^{-1}$) within the European iron and steelmaking industry. However, the deployment of bio-CCS is not the most favourable technology for all plants in terms of meeting low EU emission reduction targets. As Figure 7 demonstrates, the deployment of biomass on its own is a key strategy to reduce up to 20% (38 Mt_{CO_2} $year^{-1}$) of the total CO_2 emissions coming from integrated European steel plants. In addition, all countries provide a similar share of CO_2 emission reduction in relation to their total emissions for the lower targets. This demonstrates that no individual country would present an outstanding opportunity for the quick introduction of low-cost biomass that would in turn help to significantly reduce the total iron and steelmaking related emissions in the EU. Rather, the results show that a collaborative effort from all plants is necessary. For targets above a 20% reduction, a new technology (CCS) is introduced on top of the old one (from here on referred to as bio-CCS), particularly for plants in the Netherlands, France, Sweden and Belgium. At a 50% emission reduction target, the bulk of the reduction is met by installations of bio-CCS, which becomes the key technology for meeting any targets beyond the 50% mark. Germany and the United Kingdom (UK) are the last countries seen to introduce a shift from biomass to bio-CCS. The figure also shows that no country introduces CCS without also including biomass at any target. These results demonstrate that for European integrated steel plants, biomass or bio-CCS is preferable over the deployment of CCS alone.

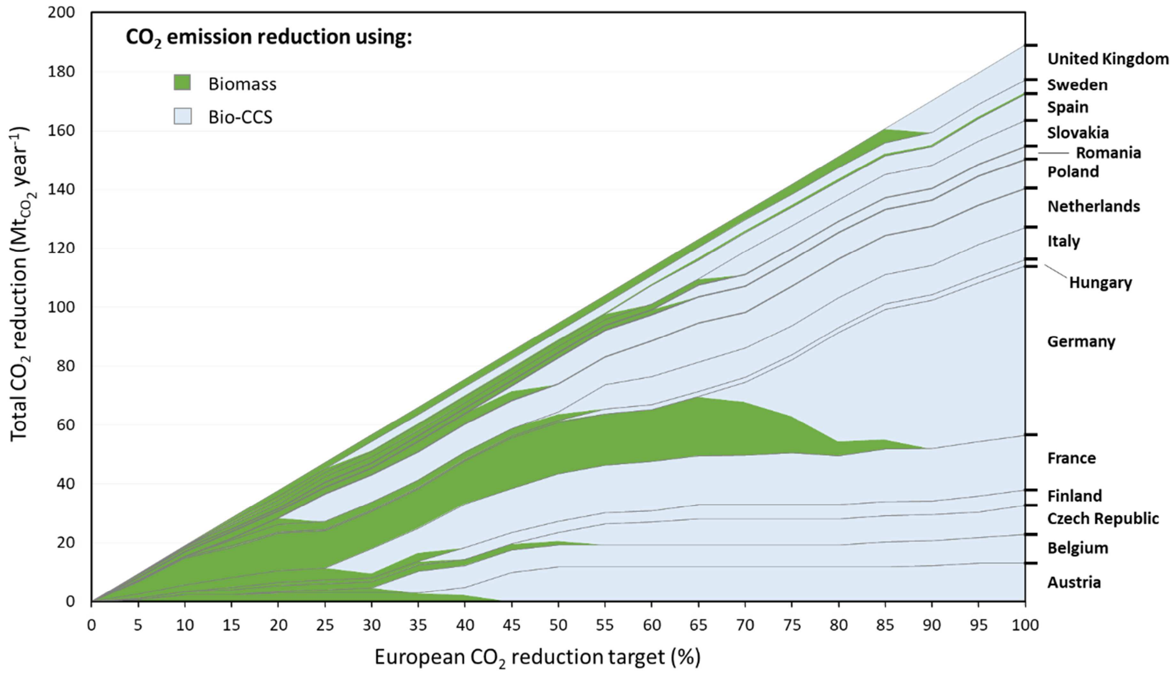


Figure 7: Changes in the technology mix based on different targets imposed on total CO_2 emissions from the European iron and steel plants. Pure CCS technology is not represented as it was never selected.

Overall, the resulting maximum achievable emission reduction for the steel plants is 191 Mt_{CO_2} $year^{-1}$, which would lead to a negative emission potential of 2 Mt_{CO_2} $year^{-1}$. This result, however, cannot be seen as significant due to the estimated error range of the obtained results, and so no negative emission opportunities across the European iron and steel industry are presented.

3.2 CO_2 avoidance cost of bio-CCS

Figure 8 shows that the CO_2 avoidance cost of emissions due to the deployment of biomass and of CCS within a bio-CCS system are comparable on plant level, particularly when comparing high levels of biomass substitution with the lowest costs of CCS deployment.

Complete CO_2 emission reduction across European iron and steel plants using bio-CCS will cost on average €80 $t_{CO_2}^{-1}$ avoided, ranging from €59 $t_{CO_2}^{-1}$ for a plant in France to €97 $t_{CO_2}^{-1}$ for a plant in the UK.

The range of the CO_2 avoidance costs of bio-CCS is due to different economics behind the deployment of biomass and CCS in each plant. For example, avoiding CO_2 emissions using biomass costs on average €61 $t_{CO_2}^{-1}$ at the maximum technically-feasible substitution. For the plant in Romania however, the CO_2 is avoided using biomass at costs as low as €40 $t_{CO_2}^{-1}$. The lower estimate of the CO_2 avoidance cost using biomass for certain plants can be explained by a combination of factors, including the availability of cheap feedstock in the plant vicinity, short transport distances between the feedstock supply locations and the plant, or competitive prices for feedstock upgrading to the final bio-products in the countries where the plants are located.

The economics of CCS on the other hand, are influenced by the distance of the plants to the storage locations, the amount of CO_2 transported annually, the type of CO_2 storage reservoir, as well as country-specific electricity prices. The resulting average CO_2 emission reduction cost using CCS technology is estimated at €92 $t_{CO_2}^{-1}$ avoided. This cost includes the technology investment, as well as the operational cost related to CO_2 capture, transport and its injection into the reservoirs. In general, CCS deployment is the most expensive for plants in Germany and the UK, as the biggest expense related to CCS deployment is the CO_2 capture cost (around 76% of the overall CO_2 avoidance cost), which is heavily influenced by the cost of electricity in the country.

Initial biomass substitution is cheaper than the deployment of CCS, as the CO_2 avoidance cost for CCS technology exceeds the CO_2 avoidance cost for initial biomass substitution, as presented in Figure 8. However, plants in the Netherlands and Belgium have CO_2 avoidance costs by bio-CCS that exceed the costs of CCS on its own (€67 $t_{CO_2}^{-1}$ and €64 $t_{CO_2}^{-1}$ for the Netherlands, and €81 $t_{CO_2}^{-1}$ and €71 $t_{CO_2}^{-1}$ for Belgium, for bio-CSS and CCS, respectively). In these cases, biomass is economically preferable to CCS for only very low emission reduction levels, and the introduction of CCS on top of biomass is expected even at lower emission targets, before the maximum technically feasible substitution by biomass is achieved. It is important to note that zero emissions across European integrated steel plants can only be reached at maximum biomass substitution in combination with full CCS deployment.

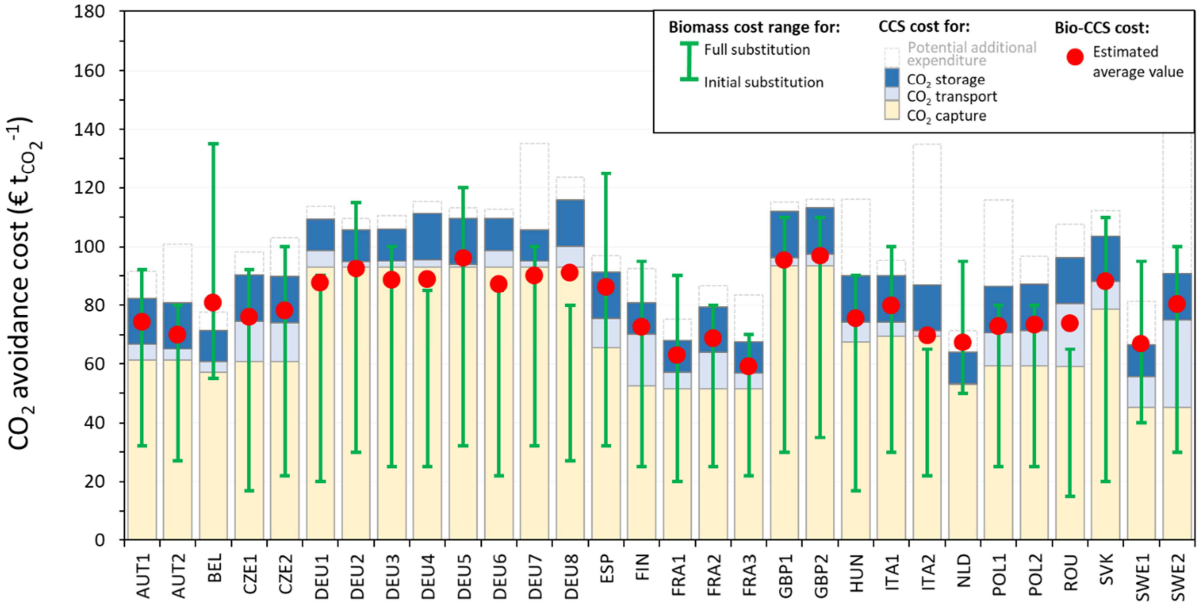


Figure 8: CO_2 avoidance cost of bio-CCS application for each plant achieved when meeting different CO_2 reduction targets across the whole European iron and steel industry.

3.3 The role of CO_2 transport and possibilities for cost reduction

CO_2 transport cost constitutes only a relatively small part of the CO_2 avoidance cost using bio-CCS, (on average 6% of the total cost). The potential reduction of the CO_2 transport cost when applying a collaborative CO_2 pipeline network instead of an individual one is studied in Figure 9. The figure demonstrates both plants for which collaborative networks will not provide any significant CO_2 transport cost benefits (plants located close to the central line), and plants for which cluster networks will result in significant reductions of the CO_2 transport costs (plants in the coloured area). As can be observed, the biggest iron and steel plants (located in the zoomed-in box of transport costs of €7 $t_{CO_2}^{-1}$ or less) do not significantly divert from the central slope line. Hence, it can be seen that the big iron and steel plants would not gain a significant economic advantage from collaborative CO_2 pipeline networks, due to the large volumes that will be transported from these plants already. On the other hand, collaborative CO_2 networks would significantly benefit smaller iron and steel plants. Cost reductions exceeding 60% could be expected for the small plants in Austria, Hungary and Poland, while for the smallest plants in Germany and Italy, the results show possible cost reductions of over 90%. Medium plants in Slovakia, Czech Republic, Finland, etc. could also benefit from collaborative pipeline networks, with transport cost reductions between 10 and 20%. The Swedish plant in Oxelösund (SWE2) is the only plant for which a collaborative pipeline network would be unprofitable, due to a significant increase in the total CO_2 transport distance from this plant. Potential storage sites have been identified in the Swedish part of the Baltic Sea, just 250 km southeast of the Oxelösund plant but storage and injection capacity in these reservoirs are still highly uncertain due to a lack of data (Rokke et al., 2016). Moreover, both potential storage sites identified in the Swedish part of the Baltic Sea are classified as Natura 2000 areas which possibly could have effect on activities related to transport and injection of CO_2(Natur Vards Verket, 2018).

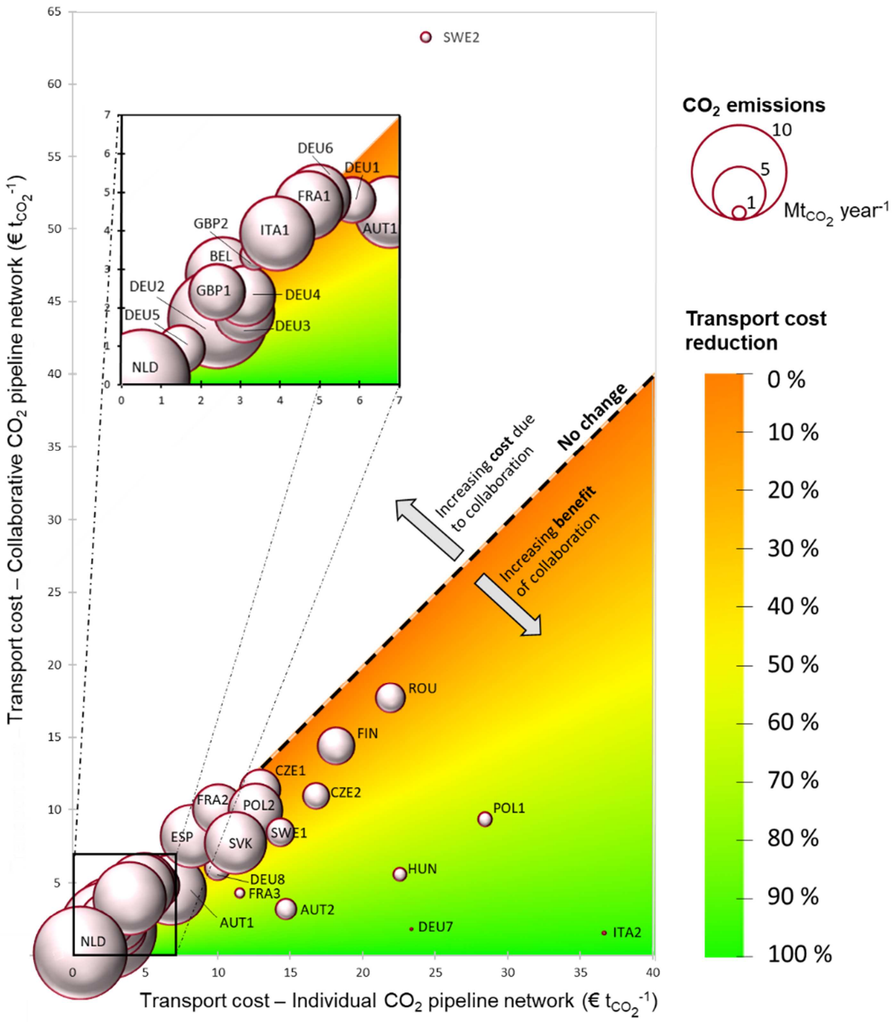


Figure 9: Impact of collaborative CO_2 pipeline network on CO_2 transport cost, compared to individual networks. Plants located close to the bottom right corner would experience the greatest cost reduction from the collaborative pipeline network. The closer a plant gets to the central line the less cost reduction per t_{CO_2} transported can be expected from joining the collaborative pipeline.

4 Discussion: Perspective for bio-CCS deployment across European integrated steel plants – from modelling to reality

The modelling results demonstrate that bio-CCS can achieve a 100% CO_2 emission reduction across European integrated steel plants. However, these results are related to the emissions occurring only on-site, and rely heavily on the assumption of carbon neutrality of biomass. As emissions of the bio-CCS system are also produced off-site due to land use change, biomass harvesting, transport and upgrading, as well as due to CO_2 capture, transport and storage, iron and steelmaking in Europe would not be carbon-neutral from the whole system perspective. For example, work by Fajardy and Mac Dowell (2017) calculated (for a specific case of US switchgrass and BECCS application) that technically, only 45% of the geologically stored biological-based CO_2 emissions could be considered as negative emissions. Therefore, the deployment of biomass or bio-CCS in the iron and steel industry could still result in a significant amount of emissions contributing to the total European carbon budget. A detailed LCA specific to each plant would be required to estimate the real environmental benefits of those technologies.

With increasing biomass demand from other sectors also looking to reduce their CO_2 emissions (e.g., as feedstock for transportation fuel production or for the chemical industry), the biomass market can be expected to undergo significant transformations, which may in turn lead to price increases. Olofsson (2018) analysed the impact on regional biomass markets of introducing biomass to an integrated steel plant in Sweden (SWE1, in this study). He found that while the total welfare effect in the region would be relatively small, certain market segments, in particular regarding secondary biomass, could potentially be heavily affected, leading to significant price effects for both the steel plant and other biomass users in the region.

The introduction of bio-CCS can present a valuable opportunity for CO_2 emission reduction and the defossilisation of the European iron and steel industry, which could also be deployable on a relatively short term. The creation of an economic environment within the EU and characterised by policy certainty (for example, giving extra credits under the EU-ETS system for bio-CCS) that would make the investments in CCS/bio-CCS a strategic decision for the industry (ZEP, 2018), is key for this transition. The average CO_2 avoidance cost of €80 $t_{CO_2}^{-1}$ identified in this work would translate to a noticeable increase in steel production cost. Even though Rootzén and Johnsson (2016) argued that a carbon price of €100 $t_{CO_2}^{-1}$ would increase the price of the final steel product (e.g., a car) by only a tiny fraction, the economic disadvantage of European steel against cheap imports from particularly China, might be further enhanced. This could in turn lead to plant shutdowns, which would also create a significant impact further down the line of the value chain by, for instance, losing a high number of steel-related jobs in Europe. Therefore, bio-CCS, especially in the European iron and steel industry, will not be deployed without a valid economic case and a stable policy regime.

Apart from economic barriers, the application of bio-CCS might not be possible due a variety of social, technical and legislative issues, mostly related to CO_2 transport and storage. While the inclusion of these aspects in the modelling was outside the scope of this work, it is, however, still important to highlight them. The integrated steel plants would have to overcome issues such as negative public perception, uncertainties in CO_2 storage capacities around Europe, issues related to the 1996 London Protocol, and temporary bans on onshore CO_2 storage in some countries, even though these issues are occurring outside of their borders. However, as has been shown in this work, the costs of CO_2 transport and storage constitute minor contributions towards the total cost of CCS/bio-CCS deployment, and non-economic barriers related to those parts might be of decisive importance.

If bio-CCS is excluded as a technology option, the maximum emission reductions are limited to 20% by exclusively using the best presently available technologies. The deployment of innovative technologies that are currently in development or pilot scales would thus be necessary to meet the targets for the iron and steel industry (Pardo and Moya, 2013). Of the emerging technologies, top gas recycling, which requires the retrofitting of the existing blast furnace fleet, is closest to application (Moya and Pardo, 2013). HIsarna or direct reduction processes such as ULCORED, Midrex, HYL or ULCOWIN are also being discussed, even though their deployment is currently facing either technology readiness issues (expected by 2030 or even 2040) or economic barriers (CO_2 avoidance costs of over €100 $t_{CO_2}^{-1}$) (Pardo and Moya, 2013). Opportunities for iron ore reduction using hydrogen, such as the HYBRIT (HYBRIT, 2017) and H2FUTURE (“H2FUTURE Green Hydrogen,” n.d.) projects in Sweden and Austria, respectively, are now also becoming available. By 2035, the industry hopes to have a process in place (Vattenfall AB, 2018) that could play a leading role in European iron and steel making from 2050 onwards (Sgobbi et al., 2016). It is not possible to predict which technologies and/or combinations of technologies are likely to emerge, but emission reductions beyond 40% will still mean their co-application with CCS (EUROFER, 2013). Therefore, overcoming CCS barriers should be a priority if CCS were to become the key technology for emission reduction in this industry in the near future (ZEP, 2018). The introduction of bio-CCS could achieve high emission savings in a relatively short time, since bio-CCS requires comparatively small retrofits to plants, while the more innovative technologies still face considerable research and development before they will be ready to be deployed.

5 Conclusion

This work explores the CO_2 emission reduction potential of bio-CCS in integrated steel plants across the EU and compares opportunities for its deployment across the 30 operating plants. Our findings show that bio-CCS can play a role in achieving carbon-neutrality across these plants when considering only emissions produced on-site. However, bio-CCS would not be an economically favourable option when aiming to reach specific CO_2 emission reduction targets below 20% for which an autonomous deployment of biomass over full bio-CCS is more favourable. Therefore, biomass can be considered a strategic solution for an initial decarbonisation, of which the CO_2 emission reduction potential could be enhanced through the additional deployment of CCS (resulting in bio-CCS), if required.

In this study, an average CO_2 avoidance cost using bio-CCS in European iron and steel plants is calculated to €80 $t_{CO_2}^{-1}$. This is indeed a large additional expenditure that would significantly increase the steel production cost of the plants, even for the most suitable ones. The work shows that an initial biomass substitution is cheaper than CCS deployment, but then costs related to the high level of biomass utilisation are similar to the deployment cost of CCS. Despite CO_2 capture accounting for the biggest share of CO_2 avoidance cost by CCS, the opportunities in cost reduction actually emerge in CO_2 transport as plants start sharing CO_2 pipeline networks. Especially for small integrated steel plants, the CO_2 transport cost could be reduced by up to 90%. Opportunities for the reduction of CO_2 capture costs could also occur in the future. Cost of a first-of-a-kind capture plant is usually significantly greater than the cost of a mature nth-of-a-kind (Rubin et al., 2015). This has been demonstrated at, for example, the Shand power plant, based on lessons learnt from the Boundary Dam, or discussed in a work by van den Broek et al. (2009). Hence, there is a high likelihood that the CO_2 avoidance cost of using bio-CCS could be even lower than €80 $t_{CO_2}^{-1}$ in the future. However, in the present, a significant cost reduction of bio-CCS is difficult, and the EU has to propose stronger economic incentives that would ensure a competitive iron and steel industry in the EU, if carbon-neutrality using bio-CCS is defined as the way to go.

From specifically a geographical viewpoint, no country presents an outstanding opportunity for bio-CCS. In general, the technology is most likely to be developed in France, the Netherlands, Belgium and in one of the plants in Sweden, since these plants achieve the lowest bio-CCS deployment costs. On the other hand, the least favourable countries are Germany and the UK due to the comparably high costs of CO_2 capture.

It is important to mention that if we want bio-CCS to be developed at a large scale in Europe, non-economic barriers of a regulatory-social-environmental nature must also be resolved, or at least accounted for in the policy agenda. Further study is necessary to identify the most essential problems that the EU or specific countries and regions are facing. It is recommended that a sensitivity analysis of the impact of overcoming barriers on the CO_2 avoidance cost for each plant shown in this work be included in such a study.

6 Acknowledgements

H. Mandova would like to thank the EPSRC CDT in Bioenergy [Grant Ref: EP/L014912/1] for her studentship and acknowledge that the research was done as part of the Peccei Award at IIASA. The financial support of VINNOVA (dnr: 2017-01327), the Swedish Energy Agency (project no. 42194-1), Bio4Energy and the Natural Environment Research Council of the UK for funding the project "Comparative assessment and region-specific optimisation of GGR" (reference NE/P019900/1) is also acknowledged. All data generated in this study are included in either the paper or the supplementary material.

7 References

Arasto, A., Onarheim, K., Tsupari, E., Kärki, J., 2014. Bio-CCS: Feasibility comparison of large scale carbon-negative solutions. Energy Procedia 63, 6756–6769. https://doi.org/10.1016/j.egypro.2014.11.711

Beer, J. De, Harnisch, J., Kerssemeeckers, M., 2000. Greenhouse gas emissions from major industrial sources - III, Iron and steel production. IEA Greenhouse Gas R&D Programme, Utrecht.

Birat, J., 2010. Steel sectoral report - Contribution to the UNIDO roadmap on CCS.

Börjesson, P., Gustavsson, L., 1996. Regional production and utilization of biomass in Sweden. Energy 21, 747–764. https://doi.org/10.1016/0360-5442(96)00029-1

Borkent, B., Beer, J. De, 2016. Carbon costs for the steel sector in Europe post-2020 - Impact assessment of the proposed ETS revision. ECOFYS, Ultrecht.

[dataset] Business Insider, 2018. CO2 European emission allowances [WWW Document]. URL http://markets.businessinsider.com/commodities/co2-emissionsrechte/euro (accessed 6.20.18).

[dataset] CEPI, 2017. Key statistics 2016 - European pulp and paper industry. Brussels. URL http://www.cepi.org/publication/key-statistics-2016 (accessed 1.25.2019)

[dataset] Dees, M., Elbersen, B., Fitzgerald, J., Vis, M., Anttila, P., Forsell, N., Ramirez-Almeyda, J.,

Garcia, D., Monti, A., Glavonjic, B., Staritsky, I., Verkerk, H., Prinz, R., Leduc, S., Datta, P., Lindner, M., Zudin, S., Höhl, M., 2017. Atlas with regional cost supply biomass potentials for EU 28, Western Balkan Countries, Moldavia, Turkey and Ukraine. Project Report. S2BIOM – a project funded under the European Union 7th Framework Programme for Research. Grant Agreement n°608622. URL http://s2biom.alterra.wur.nl/doc/S2Biom_D1_8_v_1_0_23_Jan_2017_FIN.pdf (accessed 1.25.2019)

Erbach, G., 2015. Negative greenhouse gas emissions - Assessments of feasibility, potential effectiveness, costs and risks. European Parliamentary Research Service.

EUROFER, 2013. A steel roadmap for a low carbon Europe 2050. Brussels.

European Commission, 2017. Climate strategies and targets [WWW Document]. Clim. Action. URL https://ec.europa.eu/clima/policies/strategies_en (accessed 1.13.19).

European Commission, 2016. Purchasing Power Parities [WWW Document]. Eurostat. URL http://ec.europa.eu/eurostat/web/purchasing-power-parities (accessed 8.21.17).

European Commission, 2013. Action Plan for a competitive and sustainable steel industry in Europe, COM(2013) 407 final. Strasbourg.

European Commission, 2011a. A Roadmap for moving to a competitive low carbon economy in 2050, COM(2011) 112 final. Brussels.

European Commission, 2011b. Energy Roadmap 2050, COM(2011) 885 final. Brussels.

[dataset] Eurostat, 2017. Electricity prices for non-household consumers - bi-annual data (from 2007 onwards) [WWW Document]. URL http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do (accessed 8.1.18).

[dataset] Eurostat, 2016. Greenhouse gas emissions by source sector [WWW Document]. env_air_gge. URL https://ec.europa.eu/eurostat/web/climate-change/data/database# (accessed 9.10.18).

Fajardy, M., Mac Dowell, N., 2017. Can BECCS deliver sustainable and resource efficient negative emissions? Energy Environ. Sci. 10, 1389–1426. https://doi.org/10.1039/C7EE00465F

[dataset] FAO, 2016. Forestry Production and Trade - sawnwood production [WWW Document]. FAOSTAT. URL http://www.fao.org/faostat/en/#data/FO (accessed 1.14.19).

Fick, G., Mirgaux, O., Neau, P., Patisson, F., 2014. Using Biomass for Pig Iron Production: A Technical, Environmental and Economical Assessment. Waste and Biomass Valorization 5, 43–55. https://doi.org/10.1007/s12649-013-9223-1

Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., 2014. Betting on negative emissions. Nat. Clim. Chang. 4, 850–853. https://doi.org/10.1038/nclimate2392

GAMS, n.d. Minimum Spanning Tree [WWW Document]. URL https://www.gams.com/latest/gamslib_ml/libhtml/gamslib_mst.html (accessed 1.14.19).

[dataset] Global CCS Institute, 2018. CCS Facilities Database [WWW Document]. URL https://www.globalccsinstitute.com/resources/ccs-database-public/ (accessed 1.14.19).

Gough, C., Upham, P., 2011. Biomass energy with carbon capture and storage (BECCS or Bio-CCS). Greenh. Gases Sci. Technol. 1, 324–334. https://doi.org/10.1002/ghg.34

H2FUTURE Green Hydrogen [WWW Document], n.d. URL https://www.h2future-project.eu/ (accessed 1.14.19).

Hillier, F.S., 2012. Introduction to operations research, 7th ed. McGraw-Hill, New York.

HYBRIT, 2017. SSAB, LKAB and Vattenfall form joint venture company for fossil-free steel, Press release.

IEA, 2014. Energy Technology Perspectives 2014. OECD. https://doi.org/10.1787/energy_tech-2014-en

[dataset] IEAGHG, 2013. Iron and steel CCS study (Techno-economics integrated steel mill), 2013/04. Cheltenham. URL https://ieaghg.org/docs/General_Docs/Reports/2013-04.pdf (accessed 8.1.18)

IEAGHG, 2005. Building the cost curves for CO2 storage: European sector. Cheltenham.

IIASA, 2015. BeWhere [WWW Document]. URL http://www.iiasa.ac.at/bewhere (accessed 1.14.19).

International Maritime Organization, 2006. 1996 Protocol to the convention on the prevention of marine pollution by dumping of wastes and other matter, 1972.

IPCC, 2005. IPCC special report on carbon dioxide capture and storage. Cambridge University Press, New York.

[dataset] Kjärstad, J., Johnsson, F., 2007. The European power plant infrastructure—Presentation of the Chalmers energy infrastructure database with applications. Energy Policy 35, 3643–3664. https://doi.org/10.1016/j.enpol.2006.12.032

Machado, J.G.M. da S., Osório, E., Vilela, A.C.F., 2010. Reactivity of brazilian coal, charcoal, imported coal and blends aiming to their injection into blast furnaces. Mater. Res. 13, 287–292. https://doi.org/10.1590/S1516-14392010000300003

Mandova, H., Leduc, S., Wang, C., Wetterlund, E., Patrizio, P., Gale, W., Kraxner, F., 2018. Possibilities for CO2 emission reduction using biomass in European integrated steel plants. Biomass and Bioenergy 115, 231–243. https://doi.org/10.1016/j.biombioe.2018.04.021

Margriet Kuijper, I., 2011. Public acceptance challenges for onshore CO2 storage in Barendrecht. Energy Procedia 4, 6226–6233. https://doi.org/10.1016/j.egypro.2011.02.635

Meijer, K., Guenther, C., Dry, R.J., 2011. HIsarna Pilot Plant Project, in: 1st Int. Conf. on 'Energy Efficiency and CO2 Reduction in the Steel Industry.' Dussedorf.

Mintenig, J., Khabbazan, M.M., Held, H., 2017. The role of bioenergy and carbon capture and storage (BECCS) in the case of delayed climate policy - Insights from cost-risk analysis. Earth Syst. Dyn. Discuss. 1–30. https://doi.org/10.5194/esd-2017-117

Mousa, E., Wang, C., Riesbeck, J., Larsson, M., 2016. Biomass applications in iron and steel industry: An overview of challenges and opportunities. Renew. Sustain. Energy Rev. 65, 1247–1266. https://doi.org/10.1016/j.rser.2016.07.061

Moya, J.A., Pardo, N., 2013. The potential for improvements in energy efficiency and CO2 emissions in the EU27 iron and steel industry under different payback periods. J. Clean. Prod. 52, 71–83. https://doi.org/10.1016/j.jclepro.2013.02.028

[dataset] Natur Vards Verket, 2018. Kartverktyget Skyddad natur [WWW Document]. URL https://www.naturvardsverket.se/Sa-mar-miljon/Kartor/Kartverktyget-Skyddad-natur/ (accessed 1.16.19).

[dataset] Norgate, T., Haque, N., Somerville, M., Jahanshahi, S., 2012. Biomass as a source of renewable carbon for iron and steelmaking. ISIJ Int. 52, 1472–1481. https://doi.org/10.2355/isijinternational.52.1472

[dataset] Official Data Foundation, 2018. Euro inflation calculator [WWW Document]. URL https://www.officialdata.org/Euro-inflation (accessed 7.25.18).

Olofsson, E., 2019. Regional effects of a green steel industry – fuel substitution and feedstock competition. Scand. J. For. Res. 34, 39–52. https://doi.org/10.1080/02827581.2018.1543445

Pardo, N., Moya, J.A., 2013. Prospective scenarios on energy efficiency and CO2 emissions in the European iron & steel industry. Energy 54, 113–128. https://doi.org/10.1016/j.energy.2013.03.015

Pauliuk, S., Milford, R.L., Müller, D.B., Allwood, J.M., 2013. The steel scrap age. Environ. Sci.

Technol. 47, 3448–3454. https://doi.org/10.1021/es303149z

[dataset] Platts, 2017. Electric power facilities database [WWW Document]. URL http://www.platts.com (accessed 2.5.18).

Purvis, A., Vaghi, S., 2015. The European Commission’s consultation on revision of the EU emissions trading system (EU ETS) directive. Brussels.

Ranzani da Costa, A., Wagner, D., Patisson, F., 2013. Modelling a new, low CO2 emissions, hydrogen steelmaking process. J. Clean. Prod. 46, 27–35. https://doi.org/10.1016/j.jclepro.2012.07.045

Remus, R., Aguado Monsonet, M.A., Roudier, S., Sancho, L.D., 2013. Best available Techniques (BAT) reference document for iron and steel production: industrial emissions directive 2010/75/EU (integrated pollution prevention and control). Publications Office of the European Union, Luxembourg. https://doi.org/10.2791/97469

Rokke, N.A., Aarlien, R., Mazzetti, M., Haug, J.J.K., Skagestad, R., Onarheim, K., Lund, H., Kjarstad, J., Anthonsen, K.L., 2016. Building Nordic excellence in CCS. Oslo.

Rootzén, J., Johnsson, F., 2016. Paying the full price of steel – Perspectives on the cost of reducing carbon dioxide emissions from the steel industry. Energy Policy 98, 459–469. https://doi.org/10.1016/j.enpol.2016.09.021

Rubin, E.S., Davison, J.E., Herzog, H.J., 2015. The cost of CO2 capture and storage. Int. J. Greenh. Gas Control 40, 378–400. https://doi.org/10.1016/j.ijggc.2015.05.018

Sanchez, D.L., Kammen, D.M., 2016. A commercialization strategy for carbon-negative energy. Nat. Energy 1, 15002. https://doi.org/10.1038/nenergy.2015.2

Scott, V., Geden, O., 2018. The challenge of carbon dioxide removal for EU policy-making. Nat. Energy 3, 350–352. https://doi.org/10.1038/s41560-018-0124-1

Sgobbi, A., Nijs, W., De Miglio, R., Chiodi, A., Gargiulo, M., Thiel, C., 2016. How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. Int. J. Hydrogen Energy 41, 19–35. https://doi.org/10.1016/j.ijhydene.2015.09.004

Solano Rodriguez, B., Drummond, P., Ekins, P., 2017. Decarbonizing the EU energy system by 2050: an important role for BECCS. Clim. Policy 17, S93–S110. https://doi.org/10.1080/14693062.2016.1242058

Suopajärvi, H., Fabritius, T., 2013. Towards more sustainable ironmaking—An analysis of energy wood availability in Finland and the economics of charcoal production. Sustainability 5, 1188–1207. https://doi.org/10.3390/su5031188

Suopajärvi, H., Kemppainen, A., Haapakangas, J., Fabritius, T., 2017. Extensive review of the opportunities to use biomass-based fuels in iron and steelmaking processes. J. Clean. Prod. 148, 709–734. https://doi.org/10.1016/j.jclepro.2017.02.029

UNEP, 2017. The emissions gap report 2017. Nairobi.

[dataset] Uslu, A., Faaij, A.P.C., Bergman, P.C.A., 2008. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy 33, 1206–1223. https://doi.org/10.1016/j.energy.2008.03.007

van den Broek, M., Hoefnagels, R., Rubin, E., Turkenburg, W., Faaij, A., 2009. Effects of technological learning on future cost and performance of power plants with CO2 capture. Prog. Energy Combust. Sci. 35, 457–480. https://doi.org/10.1016/j.pecs.2009.05.002

van der Stel, J., Louwerse, G., Sert, D., Hirsch, A., Eklund, N., Pettersson, M., 2013. Top gas recycling blast furnace developments for ‘green’ and sustainable ironmaking. Ironmak. Steelmak. 40, 483–489. https://doi.org/10.1179/0301923313Z.000000000221

Vattenfall AB, 2018. HYBRIT: Construction start for globally-unique pilot plant for creating fossil-free steel [WWW Document]. Press Release. URL https://corporate.vattenfall.com/press-andmedia/press-releases/2018/hybrit-construction-start-for-globally-unique-pilot-plant-for-creating-fossil-free-steel/ (accessed 1.14.19).

VDEh data exchange, 2017. Working group data exchange of European sinter plants and blast furnaces, period of reference 2016, unpublished.

[dataset] World Steel Association, 2017. Steel statistical yearbook 2017. Brussels. URL https://www.worldsteel.org/publications/bookshop/product-details~Steel-Statistical-Yearbook-2017~PRODUCT~SSY2017~.html (accessed 1.25.19)

ZEP, 2018. Role of CCUS in a below 2 degrees scenario. European Zero Emission Technology and Innovation Platform.

ZEP, 2013. CO2 capture and storage (CCS) in energy-intensive industries. European Zero Emission Technology and Innovation Platform.

[dataset] ZEP, 2011. The costs of CO2 storage - Post-demonstration CCS in the EU. European Technology Platform for Zero Emission Fossil Fuel Power Plants, IEAGHG, Brussels. URL https://www.globalccsinstitute.com/resources/publications-reports-research/ (accessed 1.25.19)

ACCEPTED MANUSCRIPT