Proceedings Paper:
Mandová, H, Patrizio, P, Leduc, S et al. (5 more authors) (2020) Modelling bio-CCS deployment across iron and steel plants in Europe. In: SSRN. 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, 21-25 Oct 2018, Melbourne, Australia. Elsevier , https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3366034 .

https://dx.doi.org/10.2139/ssrn.3366034

14th International Conference on Greenhouse Gas Control Technologies, GHGT-14

21st -25th October 2018, Melbourne, Australia

Modelling bio-CCS deployment across iron and steel plants in Europe

Hana Mandova[a,b,*], Piera Patrizio[b], Sylvain Leduc[b], Jan Kjärstad[c], Chuan Wang[d], Elisabeth Wetterlund[b,e], Florian Kraxner[b], William Gale[a]

[a]University of Leeds, Leeds LS2 9JT, United Kingdom
[b]International Institute for Applied Systems Analysis (IIASA), Schloßplatz 1, 2361 Laxenburg, Austria
[c]Chalmers University of Technology, Chalmersplatsen 4, 412 58 Göteborg, Sweden
[d]Swerea MEFOS, Aronstorpsvägen 1, 974 37 Luleå, Sweden
[e]Energy Engineering, Division of Energy Science, Luleå University of Technology, 971 87 Luleå, Sweden

Abstract

Iron and steel production is highly reliant on coal, which makes integrated steel plants one of the largest single point CO_2 emitters. Technologies that would significantly reduce their coal consumption are currently still at pilot scale. Hence opportunities for bioenergy and CCS as emission reduction strategies are evaluated, as they could be directly integrated within the existing iron and steelmaking setup. At the same time, their co-application – referred to as bio-CCS – can further enhance the emission reduction potential of each one of them. This can result in low-carbon steelmaking emitting over 80% less emissions in comparison to today, which would satisfy the EU targets set for 2050.

This work gives an overview of modelling bio-CCS systems, specifically incorporated within the techno-economic BeWhere model, focusing on the deployment of bio-CCS across the integrated steel plants in Europe. The obtained results give an estimate of the average CO_2 avoidance cost of 86 € $t_{CO_2}^{-1}$, but high variation is present across the individually plants, ranging between 62 and 114 € $t_{CO_2}^{-1}$. Overall, bio-CCS provides an opportunity to achieve net-zero CO_2 emissions occurring on-site (when assuming carbon neutrality of biomass). Modelling possibilities for bio-CCS integration is complex, due to a sophisticated and unique setup of energy usage across each integrated plant together with multiple social-technical factors that may limit their CO_2 transport and storage. Introduction of numerous assumptions is hence necessary to overcome those barriers, particularly related to issues on data availability.
Keywords: Bio-CCS; bioenergy; blast furnace; EU; carbon-neutral; industry

1. Introduction

Meeting the emission reduction targets initiated by the Paris Agreement calls for decarbonization across all sectors, including the industry [1]. The iron and steel production is currently one of the most emission intensive industrial processes. In detail, the 30 integrated steel plants (which produce steel via the blast furnace-basic oxygen furnace

* Corresponding author. Tel.: +447572 10304
E-mail address: pmhm@leeds.ac.uk

route) currently operating within the EU-28 countries emit over 190 Mt_{CO_2} per year [2], which corresponds to 5% of all EU emissions. Unfortunately, technologies which would significantly reduce the industry's dependence on fossil fuels are still at the development stage. Thus, carbon capture and storage (CCS) pathways remain the only short- and mid-term CO_2 mitigation option for this sector [3]. In addition, applying CCS technology with bioenergy (referred to as bio-CCS) gives the industry an opportunity to further enhance the emission reduction potential, without requiring a significant retrofit of the plants.

The role of bio-CCS in the future decarbonization portfolios, especially in industrial processes, is highly uncertain. Currently there are only 22 large-scale CCS facilities in operation globally, capturing up to 32 Mt_{CO_2} per year and only one of them is a steel plant, located in Abu Dhabi (capturing capacity of 0.8 Mt_{CO_2} $year^{-1}$) [4]. On the other hand, bioenergy was originally used for iron and steelmaking before the industrial revolution. The large demand contributed to deforestation particularly in the United Kingdom and the need for large amount of fuel supply initiated an introduction of coal into this industry. Nowadays, bioenergy is used for iron and steel making on a significant scale only in Brazil [5]. Considering bio-CCS as a strategy for decarbonization of European steel plants requires suitability studies that would identify the opportunities and barriers for each specific plant considering its deployment. One option is to consider spatially explicit models, which study a broad range of economic and environmental aspects and allow comparison of different plants. So far, such modelling of bio-CCS or BECCS (bioenergy CCS) systems have been done mainly for power generation [6], [7]. Modelling bio-CCS for integrated steel plants is, however, more intricate as the plants have multiple energy inputs, also of different types, and CO_2 emission sources. In addition, each integrated steel plant has a unique configuration and specific technologies, which would influence its capability for emission reduction using bio-CCS.

The current work addresses this shortage of studies on bio-CCS application within installations other than power generation. Using the techno-economic BeWhere model [8], the aim is to present a modelling framework that is able to compare opportunities for bio-CCS deployment across the European iron and steel plants and identify the CO_2 balance that each plant can achieve. The objective is to develop a model which can quantify the CO_2 emission reduction potential and the CO_2 avoidance cost of bio-CCS of each integrated steel plant, taking into consideration the differences in biomass supply, transport, upgrading as well as CO_2 capture, transport and storage network for each plant. The described methodology and the obtained results are given to provide a platform that would evoke further research on this topic.

2. Methodology

Study of bio-CCS within integrated steel plants in Europe is done using the iron and steel and CCS modules, integrated into the previously developed BeWhere Europe iron and steel model [9]. The BeWhere model [8] is a techno-economical optimization model written in the commercial software GAMS [10], defined using Mixed Integer Linear Programming (MILP) and using CPLEX as a solver. It has already been extensively used for studying optimal use of biomass resources across various locations and purposes. The idea of the model is to split the studied location into equally sized grid-cells (40 km × 40 km in this case), each containing information on the biomass supply, demand as well as transport distances to other grid-cells. The objective function is to minimize the total cost of the system, whilst meeting specific emission reduction targets, set as one of the model constraints. Further details on key aspects of the BeWhere model can be found in previous publications [11], [12], used for studying biofuel production.

In this work, the iron and steel and CCS modules, which cover the corresponding technical aspects, are added to this original bioenergy focused model, expanding the objective function by the additional costs and constraints related to each module. Bioenergy, CCS or bio-CCS is then suggested for the integrated steel plants based on the targets set on the total CO_2 emissions produced from European steel sector, in the most cost-effective way.

The bio-CCS opportunities across integrated steel plants vary. Within a typical plant in the Western Europe, there are four main possibilities for biomass integration and four opportunities for CO_2 post-combustion capture from flue gases, as shown in Figure 1. Table 1 and 2 provide further details accompanying the figure. As the iron and steel module focuses specifically on the energy use of the integrated steel plant, the four possibilities for their substitution by bioenergy are listed there. The four opportunities for CO_2 capture are defined within the CCS module. Inclusion of both of those modules during modelling are required to study the bio-CCS systems.

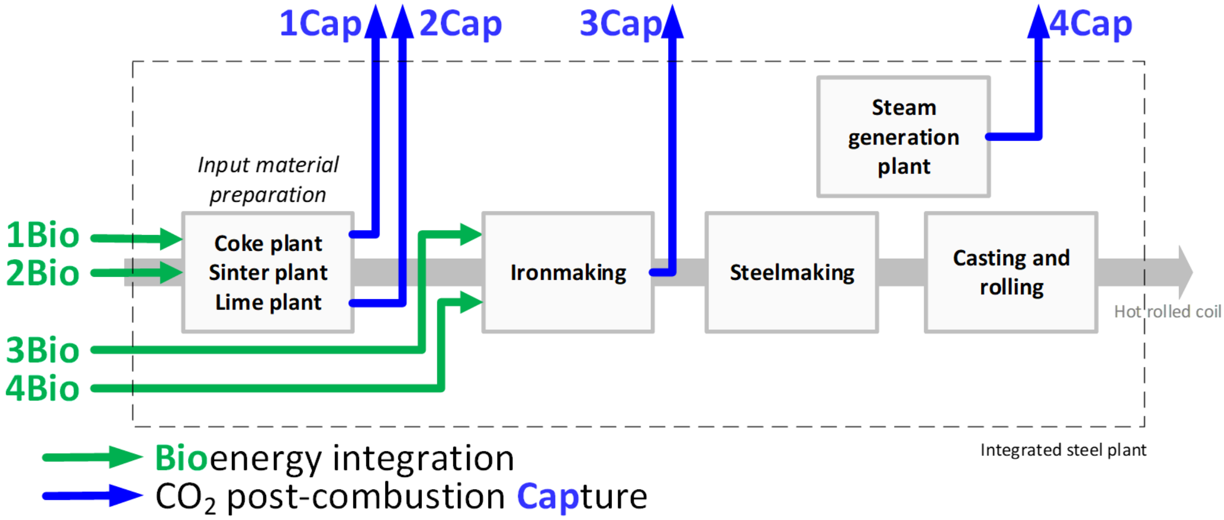

Fig. 1. Possibilities for bioenergy integration and CO_2 post-combustion capture across an integrated steel plant.

Table 1. Biomass substitution possibilities within an integrated steel plant presented in Figure 1. Values are used to define maximum substitution by biomass and the amount of CO_2 produced at each integrated steel plant.

Stage	Fossil fuel used	Fuel consumption [13]	Emission intensity [13]	Fossil fuel substitution restriction
Coke plant	(1Bio) Coking coal	13.8 GJ t_{HRC}^{-1}	0.0930 t_{CO_2} GJ^{-1}	Charcoal … max 10% [14]
Sinter plant	(2Bio) Coke breeze	1.37 GJ t_{HRC}^{-1}	0.111 t_{CO_2} GJ^{-1}	Charcoal … max 10% [14]
Ironmaking	(3Bio) Top charged nut coke	8.65 GJ t_{HRC}^{-1}	0.111 t_{CO_2} GJ^{-1}	Charcoal ... max 10% [14]
	(4Bio) PCI	4.27 GJ t_{HRC}^{-1}	0.0960 t_{CO_2} GJ^{-1}	Charcoal ….. 100% [14] Wood pellets …. max 20% [15] Torrefied fuel … max 22% [15]

*HRC = hot rolled coil

The key aspects of integrated steel plant, bioenergy and CCS, covered in the iron and steel and CCS modules, considered for modelling bio-CCS systems are:

- *Maximum fossil fuel substitution by bioenergy*

The different characteristics of bio-based fuels to fossil-based fuels limit their technically feasible substitution. Identifying the extra cost due to the use of bioenergy requires first a detailed analysis of the fossil fuel use across the plants. Specific fossil fuel consumption for producing one metric tonne of hot rolled coil (HRC) in GJ t_{HRC}^{-1} and substitution opportunities by different types of bio-based fuels in percentage on energy basis is provided in Table 1. The maximum biomass use is defined in the model using a constraint that ensures the total sum of different raw biomass feedstock supplied, and upgraded to the final bio-product, to each plant (in GJ), is less than what is technically feasible.

Table 2. Post-combustion CO_2 capture possibilities within integrated steel plants presented in Figure 1. Data from IEAGHG Iron and Steel CCS Study [13].

Stage	Flue gas from	Amount of CO_2 captured
Coke plant	(1Cap) underfired heaters	0.172 t_{CO_2} t_{HRC}^{-1}
Lime plant	(2Cap) lime kilns	0.0645 t_{CO_2} t_{HRC}^{-1}
Ironmaking	(3Cap) hot stoves	0.374 t_{CO_2} t_{HRC}^{-1}
Steam generation plant	(4Cap) steam generation	0.652 t_{CO_2} t_{HRC}^{-1}

- *Biomass supply cost*

Cost of biomass supply consists of feedstock production, its transport to the plant and upgrading. Feedstock cost depends on the type of biomass used and country of origin, averaging for this study 3.44 € GJ^{-1} [16]. Cost of its transport is done on energy basis, considering the distance, country and type of transport. Transport distances between the grid cells and evaluation of the mode of transport (truck, train or boat) are obtained using the network analysis tool in the ArcGIS software. The transport cost is split as fixed and variable cost for each transport type, where fixed cost takes into consideration only the amount of biomass used (expressed in € GJ^{-1}) and variable cost also the distance travelled (in € GJ^{-1} km^{-1}). Table 3 provides average values used for fixed and variable cost for each mean of transport.

Table 3. Average fixed and variable transport cost for biomass used in this study [17].

	Fixed cost (€ GJ^{-1})	Variable cost (€ GJ^{-1} km^{-1})
Truck	0.330	0.00123
Train	0.535	0.000310
Boat	0.330	0.000450

This study considers upgrading of raw biomass by pelletization, torrefaction and slow pyrolysis. The corresponding final bio-products (wood pellets, torrefied fuel and charcoal, respectively) are assumed to be able to partially or completely substitute the corresponding fossil fuel listed in Table 1. The substitution ratio is one-to-one on energy basis for charcoal, but 10% extra for wood pellets and torrefied fuel, due to the lower quality of those fuel types [15]. Cost of biomass upgrading to a specific bio-product varies based on the country. The country specific upgrading costs are obtained by scaling the values using purchasing power parity matrix [18]. The total upgrading costs of the final bio-products (in € GJ^{-1} of the final bio-product) is achieved by multiplying the biomass upgrading costs by the total amount of raw biomass used and energy retention efficiency of the corresponding upgrading process (which equal to 1 for pelletization, 0.9 for torrefaction and 0.65 for slow pyrolysis [19]).

CO_2 avoidance cost (€ $t_{CO_2}^{-1}$) using biomass is then achieved by subtracting the cost of the substituted fossil fuels from the cost of biomass supply and divided by the amount of emissions offset.

- *CO_2 production, capture and transport*

The amount CO_2 produced by each plant is estimated based on the different energy inputs and annual steel production. Emission intensity of each fuel (in t_{CO_2} GJ^{-1}) and amount used per metric ton of hot rolled coil is given in Table 1. The annual CO_2 emissions of a plant i, e_i, in (t_{CO_2} $year^{-1}$) are a summation of a product of annual steel production (in t_{HRC} $year^{-1}$), different amounts of fossil fuels used (in GJ t_{HRC}^{-1}) and emission intensity of each fuel (in t_{CO_2} GJ^{-1}).

The CO_2 post-combustion capture process increases the energy demand of the plant, and hence the emissions produced. It is estimated that CCS across the four flue gas sources can avoid about 60% emissions, defined here as ρ. However, the total amount of CO_2 actually captured and transported is 0.21 times higher due to the increased energy demand resulting from the CCS integration [13]. Total emissions transported from a plant for storage are therefore 0.73 times the annual CO_2 emissions of a plant.

It is assumed, based on the energy use inventory given in the IEAGHG report [13], that the additional energy demand due to installation of the capture plant will be met from the flue gases generated across the plant (coke oven gas, blast furnace gas and basic oxygen furnace gas), previously used for electricity generation. The remaining electricity demand of the plant is then met by electricity import, and so the plant's operating costs are influenced by the cost of electricity within the specific country. The CO_2 capture cost for each plant, $c_{capture,i}$, (expressed in € $t_{CO_2}^{-1}$ avoided) is derived from the IEAGHG report [13] and shown in Eq. 1. In details, it is calculated from the difference between the new ($s_{capture}$ in € t_{HRC}^{-1}) and the current ($s_{initial}$ in € t_{HRC}^{-1}) steel production cost. Both of those costs are influenced by the country-specific electricity prices that each plant i is experiencing (values in € kWh^{-1}) [20].

$$c_{capture,i} = \frac{s_{capture} - s_{initial}}{\rho \times e_i} \tag{1}$$

- *Potential CO_2 pipeline network connecting plants with CO_2 storage locations*

An inventory of suitable CO_2 storage locations around Europe can be obtained from the Chalmers CO_2 storage database [21]. In this work, a minimum spanning tree algorithm is used to minimize the overall distance that CO_2 would travel. Distances between all CO_2 sources and storage locations are calculated using ArcGIS software, and scaled by factor 1.1 or 1.2 depending on whether off-shore or on-shore pipeline network is considered. The description of the minimum spanning tree algorithm is given in the book by Hillier [22] and the GAMS code previously developed can be found online [23]. The obtained network is then used to define the CO_2 transport cost for each plant discussed in the next points.

- *CO_2 pipeline diameter*

Pipeline diameter D_i leading from plant i (in inches) is defined using Eq. 2, given in the IEAGHG report on cost curves for CO_2 storage [24], using v as the transport velocity (2.0 ms^{-1}), ρ as the density of the transported CO_2 (800 kg m^{-3}) and c as a conversion factor (from meter to inches in this case equal to 0.0254). F_i is the transported CO_2 volume (kg s^{-1}).

$$D_i = \frac{\left(\frac{4 \times F_i}{v \times \pi \times \rho}\right)^{0.5}}{c} \tag{2}$$

- *Investment cost of CO_2 pipeline*

Two types of investment costs are required when considering CO_2 network, for the pipeline and for the booster stations. The latter needed particularly to re-boost the CO_2 when transported for long distances to maintain a minimum pressure of 75 bar throughout the transport and upon arriving at the storage site. Using equations defined in the IEAGHG report on cost curves for CO_2 storage [24], one can estimate the investment cost for each specific CO_2 pipeline in €, influenced by the total length, diameter and whether the pipeline is installed on-shore or offshore.

- *Operational and maintenance cost of CO_2 pipeline*

Calculation of the operational and maintenance cost is assumed to be 3% and 5% of the investment cost for the pipeline and for the booster station, respectively [24].

- *Total CO_2 transport cost*

Defining transport cost in € $t_{CO_2}^{-1}$ requires calculation of the annual cost first, using the loan payment formula (PMT function in Excel). This formula uses discount rate (10%), operational lifetime (20 years) and present value of the investment. To the annual investment cost, operational and maintenance cost of CO_2 pipeline is added. Equation for the specific CO_2 transport cost (€ $t_{CO_2}^{-1}$) is provided in the IEAGHG report on cost curves for CO_2 storage [24], which takes into consideration the load factor (90%), total length of the pipeline and the cost of electricity.

- *CO_2 storage cost*

Costs of storage for different storage types is obtained from the Zero Emission Platform report on cost of CO_2 storage [25]. The current work considers storage only within offshore saline aquifers and offshore depleted oil and gas fields without re-usable wells, scaled by inflation, expressed in € $t_{CO_2}^{-1}$.

3. Results and Discussion

3.1. Optimal configuration of CO_2 transport network and barriers for CCS deployment

The work identified a CO_2 transport network that would connect all integrated steel plants with off-shore CO_2 storage locations in Europe. Figure 2 presents the connections between different steel plants, length of each individual pipeline onshore/offshore and locations of the sinks. Modelling of the network, based on the idea of connecting different nodes, is challenging as the model can suggest connections between plants (forming clusters) without any of them being actually connected to a CO_2 storage site. In this work, this problem is overcome by giving a possibility to connect different CO_2 storage locations too, of artificial distance smaller than any other "real" distance considered in the analysis. As the goal of the algorithm is to connect all points, each cluster will be connected to a CO_2 storage location and the connections between the different CO_2 storage locations are ignored.

The obtained modelling results demonstrate the importance of CO_2 storage in the North Sea, where building a relatively short pipeline network would be required to store as much as 77 Mt_{CO_2} annually. In other words, such network on its own would provide a potential for storage of 34% of the current CO_2 emissions from integrated steel plants in Europe. However, the London Convention prohibits export of CO_2 for storage and although an amendment to the convention has been made to allow for this, the ratification process of the amendment has turned out to be a very slow process [26, 27]. Further improvements of the modelling tool, which would take the current situation into account, is necessary to provide the evidence potentially supporting the amendment.

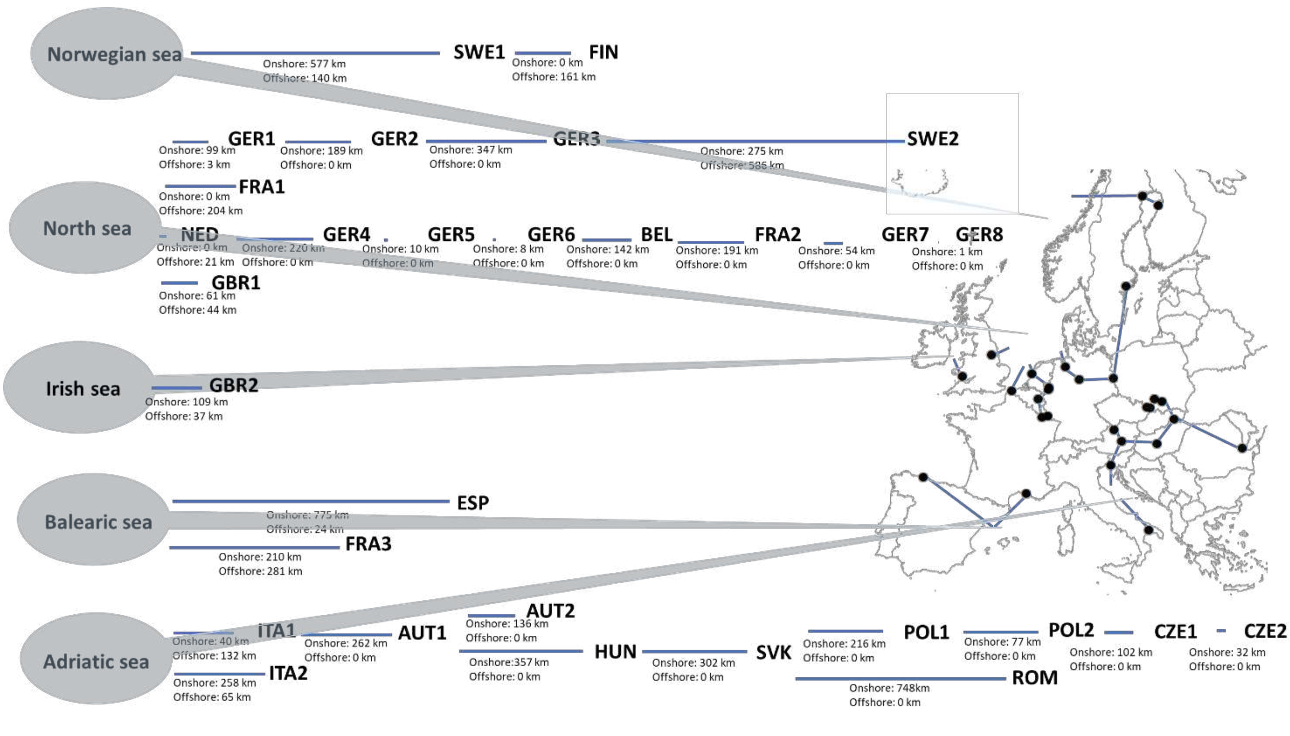

Fig 2. Optimal CO_2 pipeline network between European integrated steel plants, listing the onshore and offshore pipeline length between each integrated steel plant.

The results also demonstrate the significance of CO_2 storage within the Adriatic Sea. However, the uncertainty in its storage capacity, expensive to certify, and large pipeline network of over 2700 km leading to it requiring high capital investment as well as permissions from multiple land owners and local authorities, make such network unlikely to happen. Plants in the Eastern and South Europe hence rely on the progress in the on-shore CO_2 storage. On the other hand, European Commission work by Morbee et. al [28] suggested plants in the Czech Republic, Poland, Slovakia and Hungary should be rather connected to a CO_2 storage site in the North Sea than in the Adriatic Sea. This would, however, lead to more extensive pipeline network. On the other hand, since the countries mentioned above are landlocked, their alternative options are very limited.

3.2. Emission reduction and CO_2 avoidance cost of bio-CCS

Obtaining the CO_2 avoidance cost and emission reduction potential when using a top-down oriented system modelling approach as in this study, is limited due to lack of publicly available data. Providing such reliable estimations of fossil fuel consumption by each integrated steel plant would significantly increase the accuracy of the model results. As a consequence of the limited data availability, the results from this work compare the opportunities based on location more than based on the actual integrated steel plant set-ups.

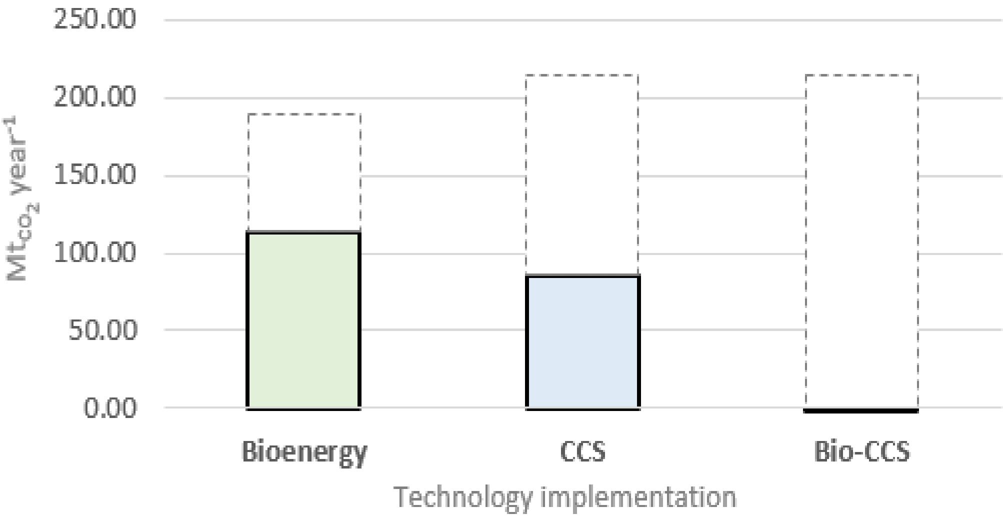

Fig. 3. Potential for CO_2 emission reduction across integrated steel plants in Europe.

The results demonstrate that bio-CCS presents an opportunity to increase emission reductions relative to what bioenergy and CCS could have achieved separately. Figure 3 shows that bioenergy by itself can reduce up to 40% of CO_2 emissions, equivalent to 75 Mt_{CO_2} year^{-1} across European plants. CCS provides an opportunity for 60% emission reduction (113 Mt_{CO_2} year^{-1}), after considering the additional CO_2 emissions generated during the CO_2 capture stage. Bio-CCS therefore presents a potential for iron and steelmaking plants to have a net carbon neutral balance of the CO_2 emissions produced on-site. However, as discussed above, the opportunities for bio-CCS are different for each individual plant. Figure 4 presents the wide range of CO_2 avoidance cost using bioenergy, CCS and bio-CCS for the integrated plants across the EU-28 countries. The results showed an average CO_2 avoidance cost using bio-CCS of 86 € $t_{CO_2}^{-1}$, ranging from 62 to 114 € $t_{CO_2}^{-1}$. The CO_2 avoidance cost of CCS on its own is 99 € $t_{CO_2}^{-1}$ and of bioenergy 67 € $t_{CO_2}^{-1}$, therefore CO_2 avoidance cost using bioenergy is generally lower. The transport cost of CO_2 is generally less than 10% of the total CCS cost, ranging from 0.2 to 21 € $t_{CO_2}^{-1}$. Only the plant in Oxelösund (Sweden) has extremely large transport cost (77 € $t_{CO_2}^{-1}$) caused by the onshore route via Germany. A better transport solution will probably be ship transport through the Baltic Sea and the North Sea [29], but ship transport has been out of the scope of this work. In addition, the actual construction of CO_2 pipeline network would be done such that other CO_2 emission sources, not only integrated steel plants, could be easily connected leading to higher volumes and lower specific cost.

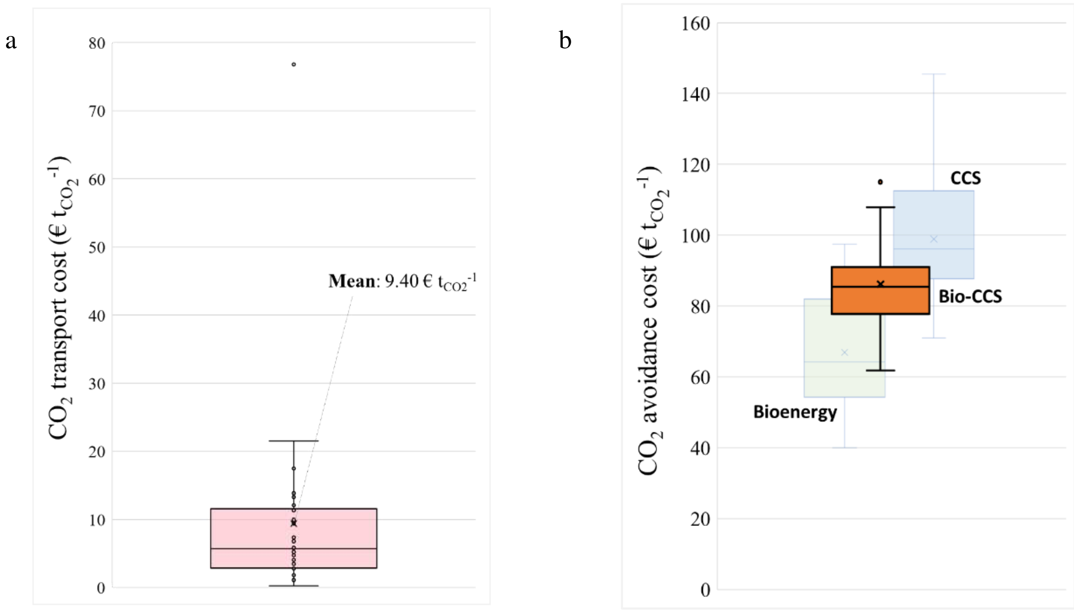

Fig. 4. (a) CO_2 transport cost range; (b) CO_2 avoidance cost of bioenergy, CCS, and bio-CCS.

4. Conclusion

Integrated steel plants are complex energy systems. Therefore, multiple assumptions and simplifications are necessary to be able to perform studies on the whole system level. When modelling bio-CCS, key cost areas to be considered are: biomass supply, transport, upgrade, and CO_2 capture, transport and storage. Due to the different geographic locations, those factors can vary significantly and hence affect the CO_2 avoidance cost for each individual plant. CCS installations also increase the energy demand. Therefore, the additional energy demand, costs and emissions produced have to be incorporated within the modelling. It is also important to consider the variation in energy prices across countries, when comparing the CO_2 avoidance cost of CCS deployment.

The results show that bio-CCS presents a unique opportunity to significantly reduce CO_2 emissions across integrated steel plants. In general, CO_2 avoidance cost by applying bioenergy is lower than by using CCS, but should be supported if and only if a sustainable supply of biomass is satisfied. In addition, bioenergy provides less problems on the implementation side, in comparison to CCS. The location of many steel plants (e.g., plants in the Eastern Europe) will complicate and raise the cost of transport systems to offshore storage sites. In terms of CO_2 storage locations, the North Sea is important for the European steel plants as well as for deployment of the CCS as a whole. The average CO_2 avoidance costs for CCS of 99 € $t_{CO_2}^{-1}$ or for bio-CCS of 86 € $t_{CO_2}^{-1}$ are currently economically unjustifiable for the European steel industry as the cost of CO_2 allowances within the EU-ETS scheme [30] are around 20 € $t_{CO_2}^{-1}$ [31]. Additional financial support for the steel plants would be required if bio-CCS is set as strategy for decarbonization of the European iron and steel sector.

Acknowledgements

H. Mandova would like to thank the EPSRC CDT in Bioenergy [Grant Ref: EP/L014912/1] for her studentship and acknowledge the research has been done as part of Peccei Award at IIASA. The Swedish Energy Agency, VINNOVA and Bio4Energy, as well as the Natural Environment Research Council of the UK for funding the project "Comparative assessment and region-specific optimisation of GGR" (reference NE/P019900/1), are also acknowledged for financial support.

As input for the analysis, this study brought together existing data in the literature and these data are referenced accordingly. All data created during this research are provided in the results section of this paper.

References

[1] M. Åhman, L. J. Nilsson, and B. Johansson, "Global climate policy and deep decarbonization of energy-intensive industries," *Clim. Policy*, vol. 17, no. 5, pp. 634–649, 2017.
[2] B. Borkent and J. De Beer, "Carbon costs for the steel sector in Europe post-2020 Impact," Ultrecht, 2016.
[3] EUROFER, "A steel roadmap for a low carbon Europe 2050," Brussels, 2013.
[4] Global CCS Institute, "CCS Facilities Database." [Online]. Available: https://www.globalccsinstitute.com/projects. [Accessed: 02-Jul-2018].
[5] J. G. M. da S. Machado, E. Osório, and A. C. F. Vilela, "Reactivity of brazilian coal, charcoal, imported coal and blends aiming to their injection into blast furnaces," *Mater. Res.*, vol. 13, no. 3, pp. 287–292, 2010.
[6] O. Akgul, N. Mac Dowell, L. G. Papageorgiou, and N. Shah, "A mixed integer nonlinear programming (MINLP) supply chain optimisation framework for carbon negative electricity generation using biomass to energy with CCS (BECCS) in the UK," *Int. J. Greenh. Gas Control*, vol. 28, pp. 189–202, 2014.
[7] F. Kraxner *et al.*, "BECCS in South Korea-Analyzing the negative emissions potential of bioenergy as a mitigation tool," *Renew. Energy*, vol. 61, pp. 102–108, 2014.
[8] IIASA, "BeWhere," 2015. [Online]. Available: http://www.iiasa.ac.at/bewhere. [Accessed: 16-Oct-2017].
[9] H. Mandova *et al.*, "Possibilities for CO2emission reduction using biomass in European integrated steel plants," *Biomass and Bioenergy*, vol. 115, no. October 2017, pp. 231–243, 2018.
[10] B. A. McCarl, A. Meeraus, P. van der Eijk, M. Bussieck, S. Dirkse, and F. Nelissen, "McCarl GAMS User Guide Version 24.6," 2016.
[11] S. Leduc, "Development of an optimization model for the location of biofuel production plants, PhD Thesis," Luleå University of Technology, 2009.
[12] E. Wetterlund, S. Leduc, E. Dotzauer, and G. Kindermann, "Optimal localisation of biofuel production on a European scale," *Energy*, vol. 41, no. 1, pp. 462–472, 2012.
[13] IEAGHG, "Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill), 2013/04," 2013.
[14] H. Suopajärvi, A. Kemppainen, J. Haapakangas, and T. Fabritius, "Extensive review of the opportunities to use biomass-based fuels in iron and steelmaking processes," *J. Clean. Prod.*, vol. 148, pp. 709–734, Apr. 2017.
[15] C. Wang *et al.*, "Biomass as blast furnace injectant - Considering availability, pretreatment and deployment in the Swedish steel industry," *Energy Convers. Manag.*, vol. 102, pp. 217–226, 2015.
[16] M. Dees *et al.*, "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.," 2017.
[17] P. Börjesson and L. Gustavsson, "Regional Production and Utilization Of Biomass in Sweden," *Energy*, vol. 21, no. 9, pp. 747–764, 1996.
[18] European Commission, "Purchasing Power Parities," *Eurostat*, 2016. [Online]. Available: http://ec.europa.eu/eurostat/web/purchasing-power-parities. [Accessed: 21-Aug-2017].
[19] UNDP, UNEP, and UNEP Risoe Centre, "Bio-carbon opportunities in eastern and southern Africa," New York, 2009.
[20] Eurostat, "Electricity prices for non-household consumers - bi-annual data (from 2007 onwards)." [Online]. Available: http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do. [Accessed: 01-Aug-2018].
[21] J. Kjärstad and F. Johnsson, "The European power plant infrastructure—Presentation of the Chalmers energy infrastructure database with applications," *Energy Policy*, vol. 35, no. 7, pp. 3643–3664, Jul. 2007.
[22] F. S. Hillier, *Introduction to operations research*, 7th ed. New York: McGraw-Hill, 2012.
[23] GAMS, "Minimum Spanning Tree." [Online]. Available: https://www.gams.com/latest/gamslib_ml/libhtml/gamslib_mst.html. [Accessed: 25-Jul-2018].
[24] IEAGHG, "Building the Cost Curves for CO2 storage: European Sector," 2005.
[25] European Technology Platform for Zero Emission Fossil Fuel Power Plants, "The Costs of CO2 Storage Post-demonstration CCS in the EU," Brussels, 2011.
[26] International Maritime Organization, "1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter," 2006.
[27] IEA, "Carbon Capture and Storage and the London Protocol: Options for Enabling Transboundary CO2 Transfer," Paris, 2011.
[28] J. Morbee, J. Serpa, and E. Tzimas, "The evolution of the extent and the investment requirements of a trans-European CO2 transport network," *JRC Sci. an Tech. Reports*, 2010.
[29] J. Kjärstad, R. Skagestad, N. H. Eldrup, and F. Johnsson, "Ship transport—A low cost and low risk CO 2 transport option in the Nordic countries," *Int. J. Greenh. Gas Control*, vol. 54, pp. 168–184, Nov. 2016.
[30] European Commission, "EU ETS handbook," 2012.
[31] Business Insider, "CO2 European Emission Allowances," 2018. [Online]. Available: http://markets.businessinsider.com/commodities/co2-emissionsrechte/euro. [Accessed: 20-Jun-2018].