Abstract

The iron and steel plants producing steel via the blast furnace-basic oxygen furnace (BF-BOF) route are one of the biggest single point emission emitters within the European Union (EU). As the iron ore reduction process is fully dependent on the provided carbon mainly supplied by coal, bioenergy is the only renewable that present an opportunity to reduce their enormous coal use. Using the BeWhere model, this work optimised the biomass resources within the EU-28 countries to identify the opportunities that bioenergy can bring to this industry.

At optimised bioenergy use, sufficient amount of resources within the EU-28 countries is present to meet the potential demand from the 30 operating BF-BOF plants, whilst satisfying the wood supply for the already existing industries. The results demonstrate, however, that bioenergy is economically unappealing and carbon price of 50 € per tCO₂ would be required to substitute 20% of the fossil fuels used across all of the BF-BOF plants. Technologies, such as hydrothermal carbonisation and pelletisation, would enhance those opportunities and emission reduction of over 4% would be already possible without any carbon price.

Different plants present different opportunities for the bioenergy integration, hence each should be treated individually. The Emission Trading Scheme therefore, may not be the best policy tool for this emission reduction strategy, as it does not differentiate between the opportunities across the plants. It also creates additional costs for the already struggling industry. Subsidies or tax reliefs might be better tools to enhance the use of renewables within this industry.

Key words: iron and steel; low-carbon steelmaking; European Union; bioenergy; waste; carbon price

Highlights

- There is enough biomass within the EU to meet the demand from iron and steel.
- Without carbon price, use of bio-products is not economically viable.
- HTC and torrefaction would enhance bioenergy opportunities.
- Over 40% emission reduction could be achieved with carbon price of 100 € per tCO₂.
- Subsidies would be better tool than the ETS to enhance bioenergy integration.
About the Author

Hana is a second year PhD student at the School of Chemical and Process Engineering in University of Leeds, UK. She is part of the EPSRC funded Centre for Doctoral Training in Bioenergy, which she has joined after finishing undergraduate degree in Mathematics at the University of Sheffield. The work she has undertaken in IIASA, summarised in this report, greatly contributes to her PhD project focusing on the opportunities and barriers for biomass integration into iron and steel industry.

Acknowledgments

Mandova would like to thank the EPSRC CDT for Bioenergy [Grant Ref: EP/L014912/1] for her studentship and acknowledge that this research was developed in the Young Scientists Summer Program at the International Institute for Systems Analysis, Laxenburg (Austria) to which the author would like to thank for the opportunity.

This work has received a fantastic supervision and support from supervisors at IIASA: Sylvain Leduc, Piera Patrizio and Florian Kraxner, and Hana greatly values their time and input. In addition, Hana is very grateful for all the feedback given by William Gale and Chuan Wang.

This reports also reflects the amazing experience at IIASA as YSSP, so Hana would like thank to all of the YSSPers and IIASA stuff for such a great time. And last but not least, Hana can’t thank enough to her family and Thomas Duffy for keeping up with all her ideas, plans and trips. She would not be able to participate at the YSSP without their great support.
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Optimisation of European biomass resources for integrated steel plants

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1 Introduction

1.1 Background

The European Union (EU) has set challenging climate targets for 2020, 2030 and 2050 to progressively reduce greenhouse gas emissions, increase share of renewable energy in the energy mix and improve the energy efficiency [1]. Those strict targets, however, require decrease of reliance on fossil fuels from all sectors – not only by electricity and heat or transport. For example, around 18% of European coal is yearly consumed specifically by the industry sector – and mostly by the iron and steel plants using blast furnace-basic oxygen furnace (BF-BOF) technologies [2]. Substituting this coal used for the iron ore reduction by renewables is challenging, as the steel production process from raw materials is mainly dependent on the solid carbon that the fossil fuels provide. As biomass is the only renewable energy that can provide such carbon and at the same time could be pre-processed and upgraded to have similar characteristics to the fossil fuels, the iron and steel industry is contemplating the viability of the solution, from the technical as well as from the resource availability point of view, as European biomass resources are greatly limited. Hence study that would focus simultaneously on the availability of biomass resources for such purpose, cost, environmental benefit as well as technical restrictions related to the fuel switching is in demand to understand the appeal of the solution for the different stakeholders involved.

The EU Best Available Techniques Reference Document for Iron and Steel Production [3] has already suggested that biomass integration for European steelmaking “should be seriously considered”, but only when its sustainable sourcing is ensured. The European project called Ultra-Low CO\textsubscript{2} Steelmaking (ULCOS) [4] – currently continuing as ULCOS II – has been already focusing on the compatibility of bio-based reducing agents with the conventional as well developing iron and steel making technologies, such as Hlsarna or ULCORED [5]. It has been observed that the different properties of biomass to fossil fuels, such as mechanical strength, reactivity, chemical composition and heating value, would allow only partial substitution across the different locations of the iron-making process using blast furnace [6]. However, pre-processed biomass, for example in the form of charcoal, could still offset up to 57% of the CO\textsubscript{2} emissions occurring on-site [7], which would be a significant reduction of national emissions for any country that has an operating BF-BOF steel plant.

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The most appealing biomass pre-treatment for iron and steel making, from the technical point of view, is by pyrolysis, as the resulting charcoal can have properties close to the used coal [8]. In Brazil, some blast furnaces are even fully operating with charcoal [9], but as the European blast furnaces are larger in size, stringent requirements on fuel properties take place, which even charcoal from woody biomass cannot fully satisfy. On the other hand, other feedstock and pre-treatment technologies can still produce a product with sufficiently high carbon content [10], even though the opportunities for substitution might be lower when compared with charcoal [11]. However, the use of bio-based product other than charcoal might be better solution for European steel industry from the biomass availability, cost and supply point of view, even though this would result in limited possibilities for the fossil fuel substitution.

The biomass availability within the EU for iron and steel making has been one of the main arguments against the technology progression. Currently, 800 000 t of charcoal is yearly consumed in Europe, primarily by the barbecue market, where 70% is already imported mainly from Africa [12]. Substituting 5% of the fossil fuels used by a smaller-European size BF-BOF plant of a production output of 3 million tonne of crude steel per year would require roughly 120 000 t of charcoal (assuming 0.8 t of coal is used per 1 t of crude steel [13]). This raises questions about the sustainability of this solution. On the other hand, the progressing forest management within the EU and forest growth being by 36% bigger than the wood consumption [14] might be able to supply the possible new demand from this industry. Additionally, even though charcoal is the most common form of biomass used for iron and steel industry, other progressing technologies are showing potential to create sufficiently high quality and suitable fuel from alternative feedstock, such as waste or agricultural residues. This includes hydrothermal carbonisation (HTC) [15] or torrefaction [16], which are already in pilot scale forms.

Studies on biomass availability for integrated steel plants have been already done for Finland [17] Sweden [18] and France [6]. Their findings indicate that sufficient amount of biomass for their iron and steel plants could be supplied, even though competition from other industries will take place. The high cost of the biomass product was identified as the most significant drawback, where higher CO₂ allowance prices would be required to make the solution economically feasible. However, steel production from those three countries account for only 15% of the EU-28 steel produced via BF-BOF route [19]. As the EU Emission Trading System (ETS) [20] and other emission reduction efforts are imposed on the integrated steel plants in the whole Europe, evaluation of biomass availability for other European plants should be done too. The European steel industry is currently missing the comparison of available resources for different plants, together with different upgrading technologies. Without this comparison, strategic use of the limited biomass resources, whilst maximising the environmental benefit, is hard to achieve. Also, the policy tools then set up with motivation to achieve certain environmental targets might not be as effective.

1.2 Aim and objectives of this work

The current work hence aims to enhance the understanding of the viability of bioenergy usage within integrated steel plants around Europe – from the resource, emission and economic perspective. Optimisation of biomass and waste resources across the EU-28 countries for the 30 currently operating integrated steel plants was done using the BeWhere model on a 40km × 40km grid level. Competition for the resources from already existing biomass industries was also considered. The outcome of this study gives an overview about
the availability of the resources, economic appeal of such solution for the plant operators as well as potential emission savings. Such information is essential for forming supportive legislation as well as identifying which technologies could bring the biggest opportunities for the biomass integration into this industry, and hence their development should be supported.

1.3 Structure of the paper

Motivation for the study has been given in this section. The next section follows with a background information on the applied BeWhere model, and optimal use of bioenergy within the EU-28 countries is then given in Results section after. Discussion whether sufficient amount of biomass resources is available, different opportunities that each plant has, the overall environmental benefit and the impact of the ETS is provided. Additionally, the paper also compares how waste-based feedstock and pilot-scale technologies could enhance bioenergy opportunities for the iron and steel industry and the additional costs that biomass integration would mean. The results indicating promising plants should awake further and more detailed studies focusing on biomass optimisation for the specific iron and steel plants on national levels.

2 Methodology

2.1 BeWhere for Iron and Steel

2.1.1 BeWhere model

As studying biomass supply for the European BF-BOF plants can be interpreted as an optimisation problem, the spatially explicit BeWhere model has been used. The BeWhere model was developed initially at IIASA and has been already extensively adapted multiple ways to study problems related to, for example, finding optimal locations for bioenergy production technologies [21, 22], decreasing energy costs [23] or examining feasibility of new technologies [24] on national as well as continental levels. The concept of the model is to split the studied location into equivalent size grid cells, where each cell contains information on the corresponding energy supply and demand within the bounded location. The grid cells are then matched so that the supply meets the demand, with an aim to minimise the overall cost. The BeWhere model is developed in the commercial software GAMS [25], uses a CPLEX solver and the studied problem is expressed via Mixed Integer Linear Programming (MILP). The core of the model is further described in the work done by Leduc [26] and Wetterlund [27].

The existing BeWhere model, however, had to be re-structured for this study to increase its flexibility when considering multiple industries with very diverse demand for the corresponding bio-products. In other words, each considered industry had very specific requirements on the quality, quantity and type of the bio-product it requires, which with the previous model set-up would result in increasing length and complexity of the model description. This work hence modified all existing industries to have a uniform structure, which can cover the diverse requirements on the bio-based products from each industry.
Figure 1: Modified structure of the BeWhere model. The figure demonstrates the interaction between the different libraries so that the final demand \(D\) is met. In detail, the model simultaneously considers all possible combinations of raw biomass materials \(RM\) and upgrading technologies \(Tech\) to produce the demanded bio-product \(BP\). Example of the flow is given for the sawmill industry.

2.1.2 Model development

The key structural change of the BeWhere model for Europe is in treating the whole system together, rather than each industry separately. In further details, a list of all considered types of:

- Raw materials \(RM_i, \ i \in \{1, \ldots, 14\}\),
- Upgrading technologies \(Tech_j, \ j \in \{1, \ldots, 7\}\),
- Bio-based products \(BP_k, \ k \in \{1, \ldots, 7\}\),
- Demand for the specific bio-product \(D_m, \ m \in \{1, \ldots, 4\}\),

within the model were listed together, rather than separately for each industry, and the selection of which of those can be used for which industry was then defined in the model input. Examples of possible relationships between each of the sections is demonstrated in Figure 1. Industries that in the previous model did not require any upgrading technology (e.g. pulp and paper mills), an artificial technology with conversion efficiency equal to 1 was created for those to still follow the structure.

2.2 Input data

Examining the bioenergy opportunities for the iron and steel industry, whilst taking into consideration the availability of the raw materials, possible upgrading technologies as well as the already existing demand from other industries required a large variety of input data. Those data were categorised either as spatial or technical. The spatial input data contains information associated to each grid point, whereas the latter were data related to the feasibility of the solution from the technical aspects. Further information about each is given in the following Section 2.2.1 and 2.2.2.
(a) Total woody biomass available per year. (b) Total bio-based waste produced per year.

Figure 2: Spatial distribution of the different availability of bio-based resources with the EU-28 countries. The dispersion of the woody biomass feedstock (left) and the bio-based waste (right) were optimised to meet the already existing demand as well as the potential demand from the iron and steel plants.

2.2.1 Spatial input

Spatial data of each studied grid point included information on the type and amount of each biomass available and the demand for specific bio-products from each industry. In total, 14 raw bio-based materials were considered. Ten of those could be classified as conventional woody biomass - such as stumps, steam wood thinning and finals, logging residues for conifer and non-conifer wood types, already included in previous studies done by the BeWhere model. The other four were newly included waste types, such as green waste, industrial food waste, municipal organic waste and sludges, collected from Eurostat database [28]. The physical and chemical properties for the waste-based feedstock are summarised in Table 1. The spatial distribution of woody biomass and waste in EU-28 is then presented in Figure 2.

Table 1: Values used for the waste-based feedstock. The selection of the considered waste types was shortlisted based on work done in [15]. The density and energy content of different waste types were obtained from the cited literature. Cost was estimated by the authors as described below.

<table>
<thead>
<tr>
<th></th>
<th>Green Waste</th>
<th>Industrial Food Waste</th>
<th>Municipal Organic Waste</th>
<th>Sludges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg m$^{-3}$) [29]:</td>
<td>148</td>
<td>593</td>
<td>178</td>
<td>721</td>
</tr>
<tr>
<td>Cost (€ t$^{-1}$):</td>
<td>70</td>
<td>80</td>
<td>30</td>
<td>0</td>
</tr>
</tbody>
</table>

*a Estimated based on the final cost of the hydrochar product defined in [15], where assuming the production cost is 80 € t$^{-1}$.

*b Cost of the waste is scaled for each country based its Purchasing Power Parity [32], where EU-28 average is taken as the base value.
The transportation cost and the associated emissions were considered independently for each type of the feedstock, same as done in previous studies where this model has been applied [22]. Maximum transport distance of 100 km and no trade opportunities between countries were assumed for the waste-based materials, as waste is usually used locally. As a result, the transport costs for the newly added waste-based materials were rather considered as fixed, i.e. 0.10 \( \text{€} \) t\(^{-1}\)km\(^{-1}\) for solid waste [33] and 0.34 \( \text{€} \) t\(^{-1}\)km\(^{-1}\) for sludge [34] and scaled based on the Purchasing Power Parity [32] within the EU-28, taking the EU-28 average value as a base.

Apart from information on the biomass availability, grid points also contained data about the already existing demand for woody biomass. In total, location and biomass demand of 276 pulp and paper mills, 182 combined heat and power plants and 268 sawmills were considered as existing industries whose biomass demand has to be met before allocating biomass for one of the 30 currently operating BF-BOF integrated steel plants. The existing biomass demand and the location of each integrated steel plant is plotted in Figure 3. Due to the technology restrictions, biomass can only partially substitute the total energy demand of the BF-BOF process. Further details on those technical constraints are described in the next Section 2.2.2.

![Graph](image)

(a) Annual woody biomass demand from existing industries. (b) Location and size of the considered integrated steel plants.

**Figure 3**: Demand for woody biomass from existing industries (left) and locations of the integrated steel plants within EU-28 countries (right).

### 2.2.2 Technical input

Substitution of fossil fuels by the bio-based fuels within an integrated steel plant is a complex problem, as there are multiple possibilities as well technical restrictions. This study considered four places within the iron-making process, where solid bio-based fuel can substitute the coal or coke. Those are demonstrated in Figure 4 and their possible substitution by different types of bio-based fuel is described in Table 3. The considered bio-based fuels result from the corresponding pre-treatment and upgrade of raw feedstock,
to achieve fuel characteristics similar to coal. The pre-treatment methods, heating values and production costs of each bio-based fuel are summarised in Table 2. The list consist of upgrading technologies, which are already commercialised, such as pyrolysis and pelletisation as well as technologies which are currently in pilot scales, such as hydrothermal carbonisation (HTC) or torrefaction. The difference in the market availability of the technologies is taken account when constructing scenarios in Section 2.3.1.

Figure 4: Coal-based fuel use during the iron-making stage and possibilities for its substitution. There are five main types of coal/coke required within the process, but only four can be substituted by biomass. Opportunities for their substitution differ between the biomass types and are described in further details in Table 3.

Table 2: Heating values and costs of the considered bio-based fuels. In total four different upgrading technologies were considered to produce potential fuel for partial substitution of the fossil fuels used by the integrated steel plants. The procedure for obtaining the listed costs is given below. Those values were then scaled for each country based its Purchasing Power Parity [32], where the listed value in this table is taken as the EU-28 base value.

<table>
<thead>
<tr>
<th>Bio-product:</th>
<th>LHV (MJ kg$^{-1}$) [35]:</th>
<th>HHV (MJ kg$^{-1}$) [35]:</th>
<th>Energy retention efficiency:</th>
<th>Investment cost (€ t$^{-1}$):$^a$</th>
<th>Operation and Maintenance (€ t$^{-1}$ year$^{-1}$):$^b$</th>
<th>Range of final product cost (€ t$^{-1}$):$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charcoal</td>
<td>31.64</td>
<td>33.67</td>
<td>0.65 [36]</td>
<td>2.677 [38]</td>
<td>4.284</td>
<td>88-407</td>
</tr>
<tr>
<td>Wooden pellets</td>
<td>19.1</td>
<td>20.5</td>
<td>1</td>
<td>0.549 [39]</td>
<td>1.758</td>
<td>34-139</td>
</tr>
<tr>
<td>HTC</td>
<td>33.67</td>
<td>23.8</td>
<td>1</td>
<td>21.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torrefaction</td>
<td>19.04 [15]</td>
<td>22.8</td>
<td>0.6 - averaged [37]</td>
<td>2.001 [38]</td>
<td>3.213</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Calculated for plant capacity of 100 t hr$^{-1}$ using formula in [38].
$^b$ Estimated as 8% of the investment cost.
$^c$ Calculated from data within the model.
Table 3: Substitution possibilities of coal or coke by bio-based fuels. The fossil fuel insertion points shown in Figure 4 and the opportunities for bio-based fuels usage were considered for charcoal, wooden pellets, hydrochar and torrefied fuel. The general heating value and possible emission saving is also listed for each individual fossil fuel type.

<table>
<thead>
<tr>
<th>Process Unit</th>
<th>Fossil fuel substituted</th>
<th>Heating value (MJ kg(^{-1})) ([40])</th>
<th>Emission factor (kg CO(_2) kg(^{-1}) fuel) ([40])</th>
<th>Possible substitution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke oven (1)</td>
<td>Coking coal</td>
<td>32.2</td>
<td>3.099</td>
<td>2-10%</td>
</tr>
<tr>
<td>Sinter Plant (2)</td>
<td>Coke Breeze</td>
<td>29.3</td>
<td>2.784</td>
<td>50-100%</td>
</tr>
<tr>
<td>Blast furnace (3)</td>
<td>Top charged nut coke</td>
<td>30.1</td>
<td>3.257</td>
<td>50-100%</td>
</tr>
<tr>
<td></td>
<td>Pulverised coal</td>
<td>31.1</td>
<td>2.955</td>
<td>0-100% 20%[18] 60%[15] 22.8%[18]</td>
</tr>
</tbody>
</table>

2.3 Scenario construction

2.3.1 Commercialised versus pilot-scale technologies

The most conventional use of biomass within the BF-BOF steelmaking process is in the form of charcoal, which requires pyrolysis pre-processing. Certain studies also considered biomass in the form of pellets, but this allows much smaller substitution possibility, see Table 3. However, progressing technologies, currently already in pilot-scales, offer opportunities for producing alternative bio-products of sufficient quality and potentially of lower cost whilst also using alternative feedstock. This work hence also included torrefaction and HTC within the analysis, but in a separate scenario to give an insight whether those can enhance bioenergy opportunities in this industry. Hence for each carbon price, two scenarios were compared:

Figure 5: Scenario construction based on commercialised and pilot-scale technologies considered within the study. As including pilot-scale technologies allowed to extend the study by waste material and upgrading technologies such as torrefaction and hydrothermal carbonisation, the work has focused on two scenarios. Scenario I considers only commercialised technologies (C) and Scenario II then extends it by technologies already in pilot-scale (C+P).
- Scenario I – where only commercialised technologies are included (i.e. pyrolysis and pelletisation); and
- Scenario II – where both commercialised as well as pilot-scale technologies are considered (i.e. also include torrefaction and HTC).

The split is shown in Figure 5. The obtained results can hence advice not only on the best use of biomass, but also answer questions whether enhanced support should be given to progressing technologies as they would be able to increase the opportunities for decarbonisation of the iron and steel industry via bioenergy.

2.3.2 On-site versus whole system

As change in the fuel supply for the BF-BOF steel plants would have an impact on the whole system, it is important to also focus on the changes occurring across different boundaries, as demonstrated in Figure 6. In detail, the attention can be only on on-site of the iron and steel plant (boundary A), on-site as well as off-site (boundary B) or on the whole system (boundary C). This is a similar difference in the approach that attributional and consequential life cycle assessments (LCA) offer as described, for instance, in [42]. To enhance the understanding of the impact of this solution on the different systems, this study tried to track the change in emissions and costs across all three boundaries. Apart from emissions due to biomass transport, carbon-neutrality was assumed and no emissions have been allocated to the bio-products production. Hence it is important to note, that this study is not a full LCA and should not be compared to one. However, understanding whether biomass use within the iron and steel industry is also a strategic decision to meet the overall EU-28 emission reduction targets and the extent that it might impact biomass supply chain for other industries can still be enhanced.

\[
\text{Whole system (C)} = \text{On-site}_s + \text{off-site}_s + \text{off-site}_e\
\]

**Figure 6:** Representation of the difference between the studied boundaries. Boundary A is focusing only on costs and emissions that occur at the iron and steel plant, where boundary B is also taking into consideration its biomass transport. Boundary C then focuses on the whole system, which includes on-site and off-site costs and emissions of the iron and steel plants, as well as off-site costs and emissions of the existing industries.
2.3.3 Impact of the carbon price

One of the main drawbacks for general implementation of the bio-based fuels is their higher cost. As the associated emission reduction is not the main motivation for the fuel switching for the industry, monetary charge for the produced emissions might be. This study hence evaluated the impact of the carbon price on the feasibility of the solution. Carbon price values between 0 and 200 € per tCO$_2$ imposed on the on-site emissions of the iron and steel plants (boundary A) were studied. The resulted costs and emissions at each boundary were then compared against a situation when no carbon price is imposed. Table 4 summarises the full focus of this study.

Table 4: Scenarios considered for this work. Carbon price of values 0 to 200 € per tCO$_2$ imposed on on-site emissions of the iron and steel plants (boundary A) was studied. Change in emissions and costs across boundary A, B and C (as defined in Figure 6) were recorded for each of the two studied scenarios: Scenario I where only commercialised technologies (C) exist and Scenario II where also pilot scale technologies (C+P) are considered. The difference between the scenarios is represented in Figure 5.

<table>
<thead>
<tr>
<th>Scenario: Carbon price imposed on the iron and steel (€ per tCO$_2$)</th>
<th>Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

3 Results

3.1 Emission reduction potential and opportunities from the pilot scale technologies

One of the main motivations for bioenergy integration into iron and steel making processes is the potential for significant emission reduction. The average emission reduction that can be achieved across all integrated steel plants in EU-28, and its sensitivity to carbon price, is shown in Figure 7. This behaviour was compared for both scenarios demonstrated in Figure 5 to identify whether technologies currently in pilot-scale can enhance the bioenergy integration or even achieve additional emission reduction, and hence whether their development should be supported.

The results show that the commercialised technologies (listed within Scenario I) offer very limited opportunities for biomass integration when no carbon price is imposed. As Figure 7 demonstrates, only 0.2% (approximately 0.6 MtCO$_2$ per year in total) of emissions across all integrated steel plants would be reduced at carbon price of 0 € per tCO$_2$. However, the pilot scale technologies (additionally included in Scenario II), would increase the emission reduction potential to 4.14% at this zero carbon price value.
Figure 7: Emission reduction across European integrated steel plants at different carbon price values. The left axis represents the average reduction across all plants as percentage of overall emissions and the right axis as sum of total emission reduced in MtCO\textsubscript{2}. Noticeable emission reduction without any carbon price is possible only with the pilot-scale technologies, however, commercialised technologies have potential to reduce more emissions when the carbon price is imposed.

With carbon prices below 40 € per tCO\textsubscript{2}, the pilot-scale technologies demonstrate better opportunities for emission reduction than the commercialised technologies. Carbon price of 40 € per tCO\textsubscript{2} is hence the threshold after which the commercialised technologies would become affordable as their greater emission savings would be worth the additional costs. The two scenarios will start to behave the same at the carbon price of 200 € per tCO\textsubscript{2}. Overall, bioenergy offers maximum emission reduction potential of 42% - averaged across all plants, which is equivalent to the total 110 MtCO\textsubscript{2} per year. The biggest change in emission reduction with increasing carbon price can be observed for values between 15 and 75 € per tCO\textsubscript{2}.

The impact of the carbon price on the type of the bio-based products used within the iron and steel industry is shown in Figure 8. For both scenarios, the charcoal is the dominant fuel whenever high carbon price is imposed. When considering only commercialised technologies (Scenario I), wooden pellets would be also used in moderate amounts. However, when extending the study by technologies currently in pilot-scale (Scenario II), the wooden pellets would be substituted by hydrochar and torrefied fuels. Figure 8b demonstrates that the emission reduction of 4.14% achieved at 0 € per tCO\textsubscript{2} (represented in Figure 7) is mainly due to the additional opportunity to use hydrochar produced from waste.
3.2 Biomass substitution opportunities at plant level

The difference in location and size gives each plant a unique biomass substitution opportunity, which was taken into consideration in this study. With the possibility to use solely commercialised technologies, only 4 plants out of the 30 operating would consider biomass substitution when no carbon price is introduced (Figure 9a). On the other hand, at the carbon price of 30 € per tCO₂, the number of plants would increase to 22. Every plant would have a certain share of bio-based fuel when carbon price exceeds value of 70 € per tCO₂. If pilot scales technologies would be also available, better opportunities for an initial fossil fuel substitution by bioenergy would be created for majority of the plants. Figure 9b shows that most of the plants would be suitable for bio-based fuel use already with carbon price of 0 € per tCO₂. Then at carbon price 30 € per tCO₂, every plant would have at least a limited potential to do so.
(a) Scenario I - Commercialised technologies only (C).

(b) Scenario II - Commercialised and pilot scale technologies (C+P).

Figure 9: Amount of fossil fuel substituted for each integrated steel plant as a function of carbon price. Scenario with only commercialised technologies (top) as well as commercialised and pilot-scale technologies together (bottom) are shown.
4 Discussion

4.1 Biomass availability within the EU-28 for iron and steelmaking

Biomass resources within the EU-28 countries could be sufficient to supply the potential bioenergy demand from all 30 integrated steel plans, however, some plants would require biomass import from other countries. Table 5 shows that particularly plants in Belgium, Czech Republic, Finland, Great Britain, Netherlands and two in Germany would be contemplating biomass imports. Comparing this against the ratio of sum of used biomass resources versus sum of biomass resources available within each country in Figure 10, it can be deduced that introduction of biomass into plants in Belgium, Finland and Netherlands would require biomass imports from other countries as the amount of biomass they produce is close to what they already consume. Study by Proskurina et al. [43] also identified Belgium and Netherlands with current biomass demand higher than potential. Hence biomass integration into those plants would not benefit local economy.

Additionally, this study has identified low availability of local resources for iron and steel application in Finland, which completely disagrees with the specifically focused study done by Suopajarvi and Fabritius [17]. These two studies roughly agree (at the theoretical level) in the total amount of woody-biomass available, especially when focusing on lower

![Figure 10: Ratio of used biomass resources relative to their availability across the country (%)](image)

**Figure 10:** Ratio of used biomass resources relative to the size of available resources within each country. Negative percentage means the country is in net sum exporting the defined share of biomass and positive percentage means the country is using such share of biomass domestically. Values above 100% indicate the country is already using more biomass resources than there are available in the whole country. The biggest undiscovered potential for bioenergy use is hence presented in countries with negative or close to zero values.
Table 5: Imported share of biomass for each individual iron and steel plant at different carbon price. Imported share of 0% indicates the plant can use exclusively local resources, whereas imported share of 100% demonstrate the plant is completely dependant on foreign resources.

<table>
<thead>
<tr>
<th>Plant</th>
<th>I - Commercialised tech (C)</th>
<th>II - Commercialised and pilot-scale tech (C+P)</th>
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<tr>
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<td>Carbon price (€ per tCO₂)</td>
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<td>-</td>
<td>-</td>
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<tr>
<td>SWE2</td>
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</tr>
</tbody>
</table>

Total BM used (PJ per year): 6.5 110.7 645.6 1204.9 1631.8 1769.9 178.0 359.6 629.9 975.5 1519.1 1769.9
Imported share (%): 0.0% 31.9% 7.2% 10.6% 24.5% 29.8% 2.2% 10.2% 10.6% 9.8% 21.6% 29.8%

estimates out of the ones that Suopajarvi and Fabritius carefully considered. However, this work identifies much bigger existing use of biomass (as of amount roughly equal to anticipated use in 2020 summarised by the mentioned authors). Similar case occurs in this study for Sweden, where high potential is concurrent with high biomass demand, which disagrees with existing studies on biomass availability [43, 44]. This demonstrates the complexity in defining the total biomass resources available and the corresponding demand for them. Studies focusing on such topics should be fully supported as they are crucial for identifying the potential for introducing bioenergy into the energy mix.

Certain countries presented sufficient amount of domestic resources, but their locations close to the boarders offers better opportunities for biomass imports. Those are specifically plants in Czech Republic, Great Britain and Germany. Overall, at the maximum potential substitution and optimal use of biomass, roughly 30% of the biomass supplied for iron
and steel plants would be imported from other EU-28 countries than the plants are in. Domestic biomass resources would be particularly used by plants in Austria, Poland, Romania and Germany, which also agrees with [43] on their biomass potential. On the other hand, Italy, Hungary and Slovakia presented in this work greater opportunities. The low potential of Scandinavian countries and high of South and Eastern European ones could be due to the type of the existing industries considered in this study. Pulp and paper, sawmills and combined heat and power plants are more common in Sweden and Finland than in the rest of Europe. On the other hand, Easter European countries could have main biomass demand from other industries (e.g. for transport fuel), which this study has not included. This might be causing false indication of the available biomass resources in those countries for such purpose. Overall, however, biomass availability across Europe does not seem to be considered as a limitation for biomass integration into the iron and steel industry.

4.2 Opportunities from pilot-scale technologies

Promotion of pilot-scale technologies and utilisation of waste by the iron and steel industry would enhance bioenergy integration into this sector, especially during low carbon prices. From Table 5 it could be observed that the total biomass use would significantly increase if pilot-scale technologies (which also give the opportunity to process waste) would become commercially viable up until carbon price 40 € per tCO₂. Particularly plants in Germany, Sweden, Great Britain and Austria would enhance their possibilities for fossil fuel substitution at the lower carbon prices. This corresponds to work done by Lorenz et al. [45], where all those countries were listed with high potential to generate energy from waste. Interestingly, this study also lists countries such as Italy and France with high waste potential, however comparing the two diagrams in Figure 9, the opportunities that pilot scale technologies would bring for plants in those countries are not as significant as for the other mentioned before. From Figure 8 it can be overall concluded that HTC and torrefaction would take a significant share in the fossil fuel substitution, and further support to their full commercialisation from the iron and steel perspective should be given.

4.3 Whole system emission reduction

The actual environmental benefit of bioenergy integration into the fossil-based systems is often questioned due to concerns about the carbon-neutrality of the fuel [46]. Those studies, however, generally omit a detailed comparison of the environmental impact of the currently used fossil fuel production (due to mining, handling and transport), and how hence the bioenergy production would be different. Comparing the environmental benefit across the whole system (as e.g. a concise LCA) was out of the scope of this study, however, Figure 11 presents the influence on the emission savings if at least the biomass transport for both iron and steel as well as existing industries is taken into account.

The off-site emissions occurring due to transport should not remarkably impact the overall benefit that bioenergy integration into the BF-BOF processes offer. In addition, as steel is a key material used in renewable technologies, it is often classified as mitigation enabler [47]. Hence significant emission reduction within the iron and steel making process will positively impact other streams that use the material, and the impact on the corresponding emission reduction in those should be considered too. This was unfortunately again, out of the scope of this study.
Figure 11: Emissions occurring across different boundaries. Biomass can significantly reduce emissions across all boundaries defined in Figure 6. As the amount of emissions is very similar for boundary A, B and C, biomass transportation for the iron and steel should not significantly impact the net environmental benefit that biomass for iron and steel offers.

4.4 Additional cost for the iron and steel as well as existing industries

Iron and steel sector is ranked between the least profitable firms from the global perspective, where specifically the European iron and steel sector belongs between the worst [48]. After the EU steel production drop in 2016, the industry has been showing signs of slow recovering in 2017 [49], but maintaining the competitive advantage still limit the investments in low carbon technologies. Hence whilst encouraging reduction of their process emissions, it is important that this won’t result in their closure. Table 6 shows how much costs related to fuel use within the iron and steel industry and costs related to biomass supply for existing industries would change with increasing carbon price.

The new demand for biomass from the BF-BOF steelmaking plants could increase the costs of biomass supply for existing by up to 10% at carbon price less than 40 € per tCO₂, and up to 20% at carbon price less than 80 € per tCO₂. This, however, is not as significant as the costs related to the iron and steel industry, which could raise by 15% at carbon price only 10 € per tCO₂. Hence carbon price might not be the best measure to promote biomass usage, as it puts additional costs on already struggling industry.
Table 6: Change in cost experienced by each sector by imposing the carbon price on iron and steel. Costs covered for iron and steel consisted of: fossil fuel costs, biomass cost and transport, as well as carbon price on on-site emissions. Costs covered for existing industries included only biomass cost and transport.

<table>
<thead>
<tr>
<th>Industry:</th>
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<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
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<th>170</th>
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<tbody>
<tr>
<td>Scenario: I - Commercialised technologies (C)</td>
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<td>50.0</td>
<td>63.9</td>
<td>74.7</td>
<td>87.0</td>
<td>98.7</td>
<td>109.6</td>
<td>119.7</td>
<td>130.0</td>
<td>140.7</td>
<td>151.1</td>
<td>160.7</td>
<td>170.6</td>
<td>180.9</td>
<td>191.1</td>
<td>201.7</td>
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<tr>
<td>II - Commercialised and pilot-scale technologies (C+P)</td>
<td>Costs compared to...</td>
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<td>2.5</td>
<td>4.8</td>
<td>8.1</td>
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<td>16.3</td>
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<td>19.7</td>
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<td>27.0</td>
<td>27.4</td>
<td>27.2</td>
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4.5 Impact of the European Emission Trading System (ETS)

The ETS is a key tool within the 2020 climate and energy package, which focuses on large-scale facilities and accounts for 45% of the EU’s greenhouse gas emissions. Its aim is to lower overall emissions in those facilities by 21% by 2020 in comparison to 2005 levels [1]. The iron and steel sector has been included within the ETS since the beginning [20], where the sector has already lowered emissions from 251 MtCO₂ to 211 MtCO₂ between 2011 and 2015. This drop, however, was mainly due to the decrease in steel production capacities and complete closures of few European integrated steel plants.

As this work indicates that bioenergy has the potential to significantly reduce emissions as well as decrease fossil fuel use by this industry – from the resource availability aspect – impact of the ETS is important to discuss. The ETS considers biomass as zero-carbon fuel, so the system does not account for any CO₂ emissions resulted from the biomass utilisation. The revised allocation of emission allowances post 2012 [50] combined the two independent benchmarks for blast furnace and basic oxygen furnace under a single hot metal benchmark. Bioenergy could be used at various parts of the process, and hence can help the integrated plants to meet specific benchmarks set specifically for cokemaking, sintermaking and now also for hot metal production as a whole. As the hot metal is the most emission intensive product across the whole iron and steel sector, which at the
same time achieved the biggest emission allowance, combining blast furnace and basic oxygen furnace under one benchmark gives more credit to bioenergy use. This is because biomass can be mainly used by the blast furnace, so plants which have inefficient basic oxygen furnace now have an opportunity to offset emissions using biomass at the most suitable location somewhere else, which would result in efficient use of resources. For the best bioenergy integration under ETS, it could be argued that all three stages: cokemaking, sintermaking and hot metal production should be under one benchmark (if they are all present within the plant site), so that biomass is used where it is the most suitable based on its properties, rather than where emission reduction is required.

On the other hand, the ETS as a policy tool might not be the best way to introduce bioenergy into the iron and steel sector. Iron and steel is highly CO\textsubscript{2} intensive, but it is also internationally traded so any additional costs (either due to emissions or purchasing alternative fuels) could impact its competitiveness. Even though some studies have argued that the ETS shouldn’t have a major impact on productivity and competitiveness of this industry [51], the ETS might not be the best way to increase bioenergy share in a sector, as discussed by Schwaiger et al. [52] for biofuels, mainly due to the price fluctuations of the allowances. Alternative instruments such as subsidies or price reliefs might be better incentives, which would be also targeting specific plants, rather than all of them the same way, as each plant has a unique opportunity for the biomass substitution. Only then, successful bioenergy integration into this industry which also benefits the local economy and ensures sustainable biomass supply could be achieved.

4.6 Limitations of the work

The current work is done to elucidate the potential of bioenergy use within the iron and steel industry from the biomass availability aspect, and hence should not be used to set any sort of benchmarks for biomass use within this industry. In addition, it considers the current production of the iron and steel, and hence any future development changes within this sector have not been accounted for. Also, the coal and biomass prices are greatly volatile, hence the computed carbon price values are only approximates and should be evaluated in great details before carbon price is used to increase share of renewables within this sector.

The precision of the results was also reduced by treating each integrated steel plant with the same possibilities for the biomass substitution. Listing separately the specific technologies they contain on-site as well as off-site and optimising the biomass based on the corresponding opportunities they present would provide more accurate values. The model was developed so that it can take this into account, however the sensitivity of the data for each plant did not allow to undertake such research at this point. This study was hence focusing on the supply side of the problem and so have not addressed whether all substitutions are technically feasible at the listed rates in Table 3.

Lastly, the work has considered only three main industrial biomass consumers. However, transport biofuels account for a great share of the European biomass demand, which this project has not accounted for. Hence any conclusions done based on this study should take into a consideration that there is a larger competition for the biomass resources around Europe than this study has considered.
4.7 Future work

A follow-up study is planned to compare the bioenergy as a strategy against other emission reduction technologies listed for the European BF-BOF steelmaking plants. Comparison of the costs, feasibility and emission reduction potential for each will be given. The work described in this paper had not had a possibility to include the Carbon Capture and Storage (CCS) for the iron and steel to identify whether BECCS (CCS with Bioenergy) would present better opportunities, and hence whether bioenergy should be considered if and only if CCS technologies are used too. The CCS for the iron and steel industry is listed between the long-term emission reduction strategies, and understanding the full potential is hence crucial to achieve the set environmental goals, but at the same time preserving competitive advantage of the industry.

5 Conclusion

5.1 Summary

Iron and steel plants – and especially those using blast furnace-basic oxygen furnace (BF-BOF) technologies – are one of the main consumers of coal in Europe. Motivation to introduce renewables into the iron-making processes are limited to biomass, as only this type can produce solid carbon required for the iron ore reduction. The limited biomass resources within Europe, however, has put question-mark onto the feasibility of the solution from the biomass availability point of view. This study was done to explore aspects that present the biggest barriers for the biomass integration into European iron and steel making plants.

The available biomass was optimised to meet the demand from the existing industries as well as the potential demand from the 30 currently operating BF-BOF plants within the EU-28 countries. At zero carbon price, and considering only commercialised technologies, only four plants would be suitable for the biomass integration. However, pilot-scale technologies (which would allow also waste use) could enhance opportunities for bioenergy use for most of the plants. The HTC and torrefaction hence present an additional opportunity for bioenergy integration into the iron and steel industry, especially for lower share of fossil fuel substitutions. Overall, within the EU-28 countries there is a sufficient amount of biomass resources to meet the potential demand from the iron and steel industry, but biomass trade between the countries would be required.

Bioenergy use within the BF-BOF plants has the potential to reduce over 40% of the emissions resulting from the fossil fuel use. To achieve this though, biomass in the form of charcoal and carbon price over 100 € per tCO₂ would be required. With the commercialised technologies, every plant would consider a certain share of biomass at 60 € per tCO₂. Including pilot-scale technologies, the carbon price would have to be only 30 € per tCO₂. Carbon price of roughly 50 € per tCO₂ would be required to achieve fossil fuel substitution of 20% – the EU target for 2020.

5.2 Policy implication

Use of bioenergy within the iron and steel industry is a matter of cost, rather than biomass availability. The successful integration would require biomass trade between the European
countries to meet such high demand from the specific plants. However, as the net environmental benefit is not impacted notably by the transport, biomass trade for such purpose should be supported. Pilot scale technologies can significantly enhance bioenergy integration opportunities, hence support for the HTC and torrefaction should be given. Achieving 20% of fossil fuel substitution – overall goal set by the EU by 2020 – across the 30 integrated steel plants would require carbon price of minimum 50 € per tCO₂. However, imposing carbon price on the iron and steel plants might initiate biomass use, but also significantly impact their profitability as well as increase the biomass supply cost for existing industries. Hence the ETS is not the best tool for bioenergy integration, and other measures such as subsidies or tax reliefs might be a better option to ensure the European products can compete with the cheap imports.

References


[43] S. Proskurina, R. Sikkema, J. Heinimo, and E. Vakkilainen, “Five years left – How are the EU member states contributing to the 20% target for EU’s renewable energy consumption; the role of woody biomass,” *Biomass and Bioenergy*, vol. 95, pp. 64–77, 2016.


