Biomass and Bioenergy 115 (2018) 231–243

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Research paper

Possibilities for CO_2 emission reduction using biomass in European integrated steel plants

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ARTICLE INFO

Keywords:
Iron and steel
Low-carbon steelmaking
BF-BOF
Bioenergy
Carbon price
Optimisation

ABSTRACT

Iron and steel plants producing steel via the blast furnace-basic oxygen furnace (BF-BOF) route constitute among the largest single point CO_2 emitters within the European Union (EU). As the iron ore reduction process in the blast furnace is fully dependent on carbon mainly supplied by coal and coke, bioenergy is the only renewable that presents a possibility for their partial substitution. Using the BeWhere model, this work optimised the mobilization and use of biomass resources within the EU in order to identify the opportunities that bioenergy can bring to the 30 operating BF-BOF plants.

The results demonstrate competition for the available biomass resources within existing industries and economically unappealing prices of the bio-based fuels. A carbon dioxide price of 60 € t^{-1} is required to substitute 20% of the CO_2 emissions from the fossil fuels use, while a price of 140 € t^{-1} is needed to reach the maximum potential of 42%. The possibility to use organic wastes to produce hydrochar would not enhance the maximum emission reduction potential, but it would broaden the available feedstock during the low levels of substitution.

The scope for bioenergy integration is different for each plant and so consideration of its deployment should be treated individually. Therefore, the EU-ETS (Emission Trading System) may not be the best policy tool for bioenergy as an emission reduction strategy for the iron and steel industry, as it does not differentiate between the opportunities across the different steel plants and creates additional costs for the already struggling European steel industry.

1. Introduction

The European Union (EU) has set climate targets for 2020, 2030 and 2050 to progressively reduce greenhouse gas emissions up to 80%, by increasing the share of renewable energy in the energy mix and improving energy efficiency [1]. These strict targets, however, require decreasing reliance on fossil fuels from all sectors – not only for electricity, heat and transport. For example, around 18% of all coal consumed in the EU, by countries part of the OECD, is used by the industrial sector – and mostly by iron and steel plants using the blast furnace-basic oxygen furnace (BF-BOF) route [2]. Substituting the 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 coal-based fuels provide. Biomass is the only renewable feedstock that can provide such carbon and at the same time could be upgraded to have similar (although not identical) characteristics to fossil fuels [3]. The iron and steel industry is therefore contemplating the viability of the use of biomass [4], from a technical as well as from the resource availability point of view, as European biomass resources are greatly limited, and it would be desirable to avoid the emissions associated with the long-distance transport of biomass.

The present paper undertakes a study that focuses simultaneously on the availability of biomass resources that are also in demand for other applications, their cost and potential environmental benefits, as well as technical restrictions related to fuel switching. Our intent is to identify the extent to which biomass has the potential to meet the needs of the different stakeholders involved, i.e. the decision makers from the iron and steel industry as well as policy makers interested in reducing the fossil fuel use in the sector.

The EU *Best Available Techniques Reference Document for Iron and*

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https://doi.org/10.1016/j.biombioe.2018.04.021
Received 20 October 2017; Received in revised form 26 April 2018; Accepted 26 April 2018

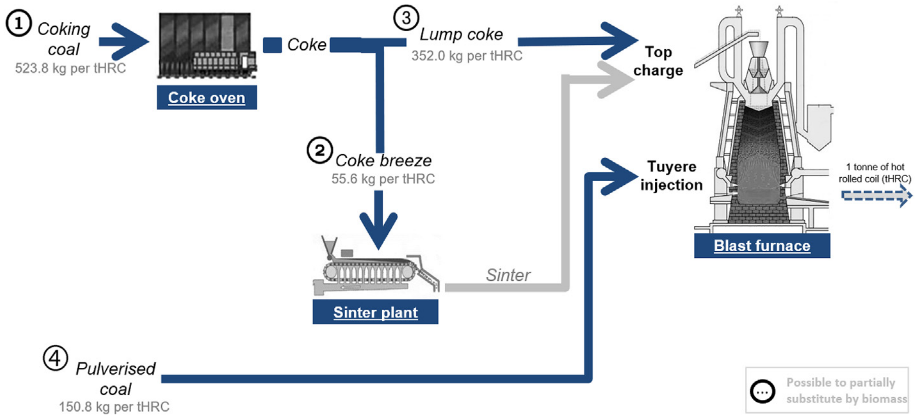


Fig. 1. Coal-based fuel flow during the iron-making stage.

Table 1
Substitution possibilities of coal or coke by bio-based fuels.

Process Unit		Fossil fuel substituted	Heating value ($MJkg^{-1}$) [31]	CO_2 emission factor for fossil fuel ($kg\,kg^{-1}$) [31]	Fuel cost (€ GJ^{-1}) [31]	Possible substitution			
						Charcoal [29]	Wood pellets	Hydrochar	Torrefied fuel
Coke oven	(1)	Coking coal	31.10	2.89	3.98	2-10%	–	–	–
Sinter Plant	(2)	Coke Breeze	29.01	3.23	5.35	50-100%	–	–	–
Blast furnace	(3)	Top charged nut coke	29.01	3.23	5.35	50-100%	–	–	–
	(4)	Pulverised coal	33.37	3.19	3.17	0-100%	20% [21]	25% [18]	22.8% [21]

Steel Production [5] 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_2 Steelmaking (ULCOS) [6] has focused on the compatibility of bio-based reducing agents with conventional as well as emerging iron and steel making technologies, such as HISARNA or ULCORED [7]. The different properties of biomass to fossil fuels (such as mechanical strength, reactivity, chemical composition and heating value) would allow only partial substitution of coal used across the ironmaking process of the BF-BOF route [8]. However, pre-processed biomass, for example in the form of charcoal, could still offset up to 57% of the CO_2 emissions occurring on-site [9], which would be a significant reduction of national emissions for any country that has an operating BF-BOF steel plant.

The most appealing biomass pre-treatment for iron and steel making, from the technical point of view, is by slow pyrolysis, as the resulting charcoal can have properties close to the conventional coal [10]. Certain plants in Brazil are already fully operating with charcoal in small blast furnaces [11], but as European blast furnaces are generally larger in size (both in diameter and height), stricter requirements on fuel properties take place and charcoal therefore presents opportunities only for partial substitution. Other bio-based products (e.g. wood pellets) could also contain sufficiently high carbon content [12], but their characteristics present even lower fossil fuel substitution possibilities than charcoal [13]. On the other hand, those bio-based products might present better bioenergy opportunities for European steel industry from the biomass availability, cost and supply aspect.

The biomass availability and its sustainable sourcing for the European iron and steel making has been among the main arguments against the technology progression [14]. Currently, 800 kt of charcoal is yearly consumed in Europe, primarily by the barbecue market, where 70% is already imported mainly from Africa [15]. Substituting 5% of the fossil fuels used by even a small European size BF-BOF plant of a production output of 3 million tonnes of crude steel per year would require roughly 120 kt of charcoal (assuming 1:1 substitution of coal by charcoal, where 0.8 t of coal is used to produce 1 t of crude steel [16]). This raises questions about the sufficiency of EU resources for deployment of this solution. On the other hand, the enhanced forest management within the EU and commercial forest growth being around 36% bigger than current EU sourced wood consumption [17] might be able to supply the possible new demand from this industry. Additionally, even though charcoal is the most common form of biomass studied for the iron and steel industry, other progressing technologies are showing potential to create sufficiently high quality and suitable fuel from alternative feedstock, such as organic wastes or agricultural residues. Those include hydrothermal carbonisation (HTC) [18] and torrefaction [19], which are currently in pilot scale forms.

Studies on biomass availability for integrated steel plants have already been done for Finland [20], Sweden [21] and France [8]. The findings indicate that sufficient amount of biomass for their iron and steel plants could be supplied using their national resources, even though competition from other industries will take place. The high cost of the biomass product was identified as the most significant drawback, where the current CO_2 allowance prices do not make the solution economically feasible. However, steel production from those three countries accounts for only 15% of the EU-28 steel produced via BF-BOF route [22]. As the EU Emission Trading System (EU-ETS) [23], aiming to lower the overall emission in large-scale facilities by 21% by 2020 in comparison to 2005 levels, is imposed on the integrated steel plants across the whole Europe, evaluation of biomass availability for other European plants should also be done. 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. In addition, the policy tools imposed with motivation to achieve certain environmental targets might not be effective.

The current work aims to enhance the understanding of the viability

Table 2
List of all raw materials, technologies, bio-products and biomass demands which were optimised within the *BeWhere Europe* model.

RM_i	Raw materials	$Tech_j$	Technologies	BP_k	Bio-product	D_m	Demand
1	Stumps - nonconifer trees	1	Preparation technology for pulp and paper (RM 3 to 6)	1	Bio-product for pulp and paper (Tech 1)	1	Pulp and Paper (BP 1)
2	Stumps - conifer trees	2	Preparation technology for heat and power plants (RM 1,2, 5 to 10)	2	Bio-product for heat and power plants (Tech 2)	2	Heat and power plants (BP 2)
3	Stemwood from final fellings - nonconifer trees	3	Preparation technology for sawmills (RM 3,4)	3	Bio-product for sawmills (Tech 3)	3	Sawmills (BP 3)
4	Stemwood from final fellings - conifer trees	4	Pyrolysis (RM 1 to 10)	4	Charcoal (Tech 4)	4	Steel plants (coking coal) (BP 4)
5	Stemwood from thinnings - nonconifer trees	5	Peletization (RM 1 to 10)	5	Wood pellets (Tech 5)	5	Steel plants (coke) (BP 4)
6	Stemwood from thinnings - conifer trees	6	Hydrothermal carbonization (RM 11 to 14)	6	Hydrochar (Tech 6)	6	Steel plants (PCI) (BP 4,5,6,7)
7	Logging residues from final fellings - nonconifer trees	7	Torrefaction (RM 1 to 10)	7	Torrefied fuel (Tech 7)		
8	Logging residues from final fellings - conifer trees						
9	Logging residues from thinnings - nonconifer trees						
10	Logging residues from thinnings - conifer trees						
11	Green waste						
12	Industry food waste						
13	Municipal waste						
14	Organic sludges						

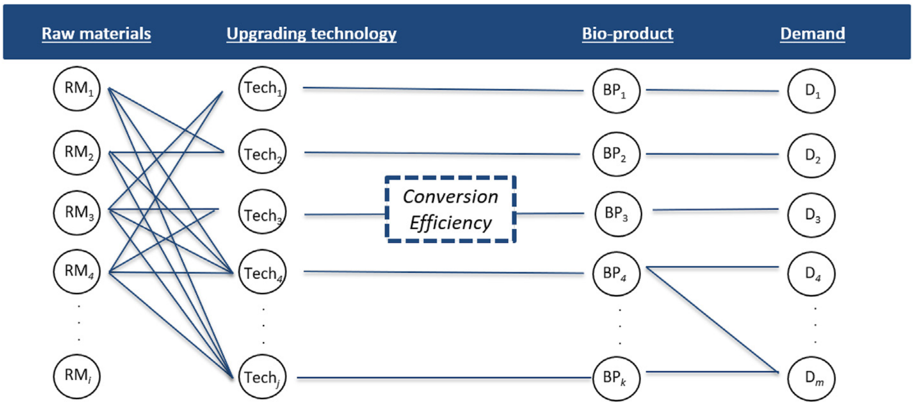


Fig. 2. Modified structure of the *BeWhere Europe* model, as used for the current work. Details on the possible combinations is given in Table 2.

Table 3
Physical and chemical properties used for the waste-based feedstock.

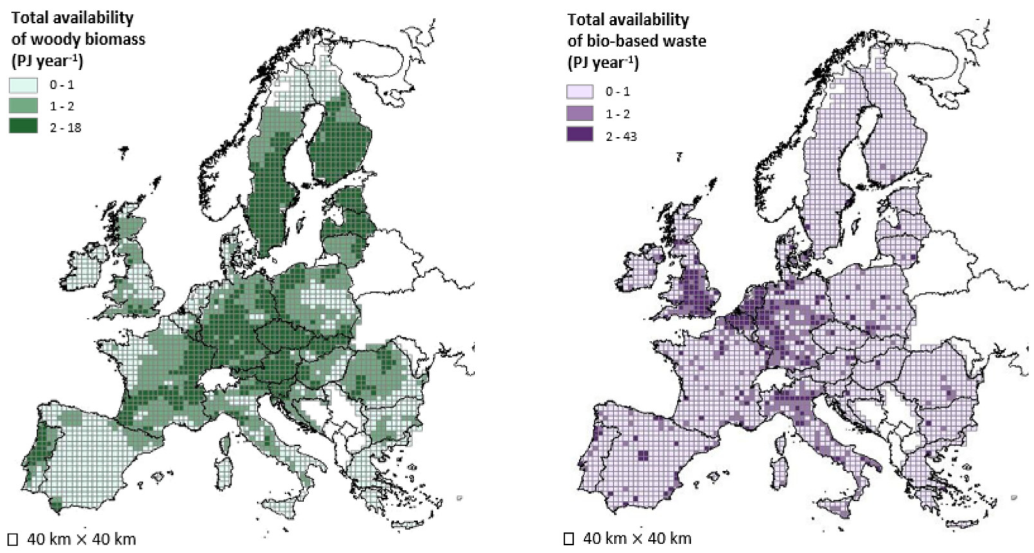
	Green Waste	Industrial Food Waste	Municipal Organic Waste	Common Sludges
Density (kgm^{-3}) [37]	148	593	178	721
Energy content ($MJkg^{-1}$)	11.9	6.0 [38]	11.4 [38]	10.8 [39]
Cost ($€ t^{-1}$)[a,b]	75	85	35	5

[a] Estimated based on the final cost of the hydrochar product defined by Wang et al. [18] and assuming the production cost of 75 $€ t^{-1}$ calculated from Ref. [40].

[b] Cost of each type of waste is scaled for each country based on its Purchasing Power Parity [41], where the EU-28 average is taken as the base value.

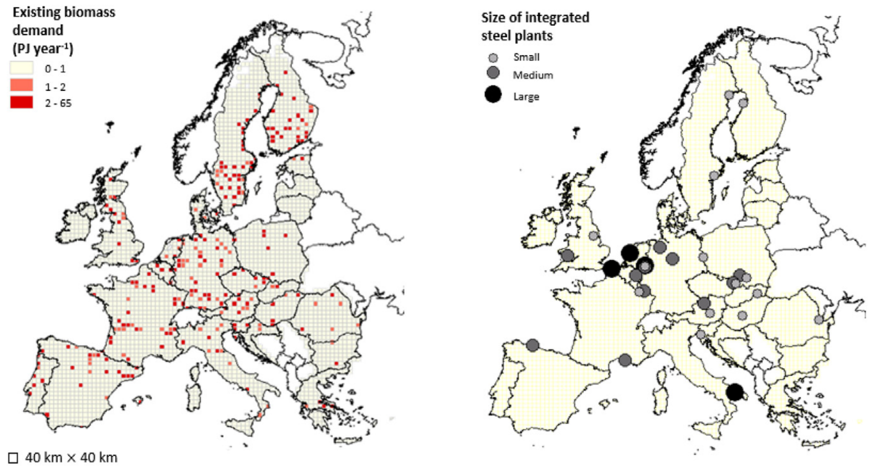
of bioenergy usage within integrated steel plants around Europe – from the resource, emission and economic perspective. Optimisation of biomass and waste resources across the EU-28 countries for the 30 currently operating integrated steel plants was done using the *BeWhere Europe* model [24]. Competition for the resources from existing biomass industries is also considered. The outcome of this study provides an overview of the availability of biomass resources, the economic appeal of such a solution for the plant operators as well as the 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. The work focuses on biomass sourced within the EU and preferably near iron and steel plants, both to reduce emissions from biomass transport and to facilitate control over the sustainability of biomass sourcing.

The next section follows with a background information on the applied *BeWhere* model. Findings about the biomass availability, CO_2 emission reduction potential and additional costs are then provided in the results section, followed by a discussion about the feasibility of bioenergy deployment within European BF-BOF plants and other opportunities for steel industry decarbonisation.



(a) Total woody biomass (b) Total bio-based waste

Fig. 3. Spatial distribution of the modelled availability of bio-based resources within the EU-28 countries.



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

Fig. 4. Demand for woody biomass from existing industries in (a) and locations of the integrated steel plants within the EU-28 countries in (b).

2. Methodology

Biomass use by integrated steel plants can significantly impact biomass availability and cost. The smallest possible impact can be assumed to occur when all industries across the EU-28 countries use biomass strategically. One way to define the strategic use of biomass is to treat the situation as an optimisation problem and the obtained solution as the optimal biomass use across European industries, based on cost. In this study, the optimal biomass use was defined using the spatially explicit *BeWhere Europe* model. The *BeWhere* model, developed initially at IIASA [24], has been extensively adapted to analyse, for example, optimal locations for bioenergy production technologies [25,26], decreasing energy costs [27] or examining feasibility of new technologies [28] on national as well as continental levels. The flexible model structure presented opportunities for adopting the model to also study possibilities for biomass utilisation within integrated steel plants, which has been the task for this work. In addition, the model had already incorporated input data related to biomass availability and demand, which allowed detailed evaluation of the potential impact of iron and steel plants on biomass use in Europe.

2.1. Biomass opportunities within iron and steel making

Modelling substitution of fossil fuels by bio-based fuels within an integrated steel plant is complex due to multiple possibilities as well as technical restrictions. Four main coal-based inputs within the iron-making process are present, which can be fully or partially substituted by bio-based fuel [20]. Those coal-based inputs are (1) coking coal used in the coke ovens, (2) coke breeze used at the sinter plant, (3) nut coke charged at the top of the blast furnace and (4) pulverised coal injected (PCI) via tuyeres in BF, as shown in Fig. 1. Table 1 summarises the substitution possibilities of coal or coke by bio-based fuels. The most

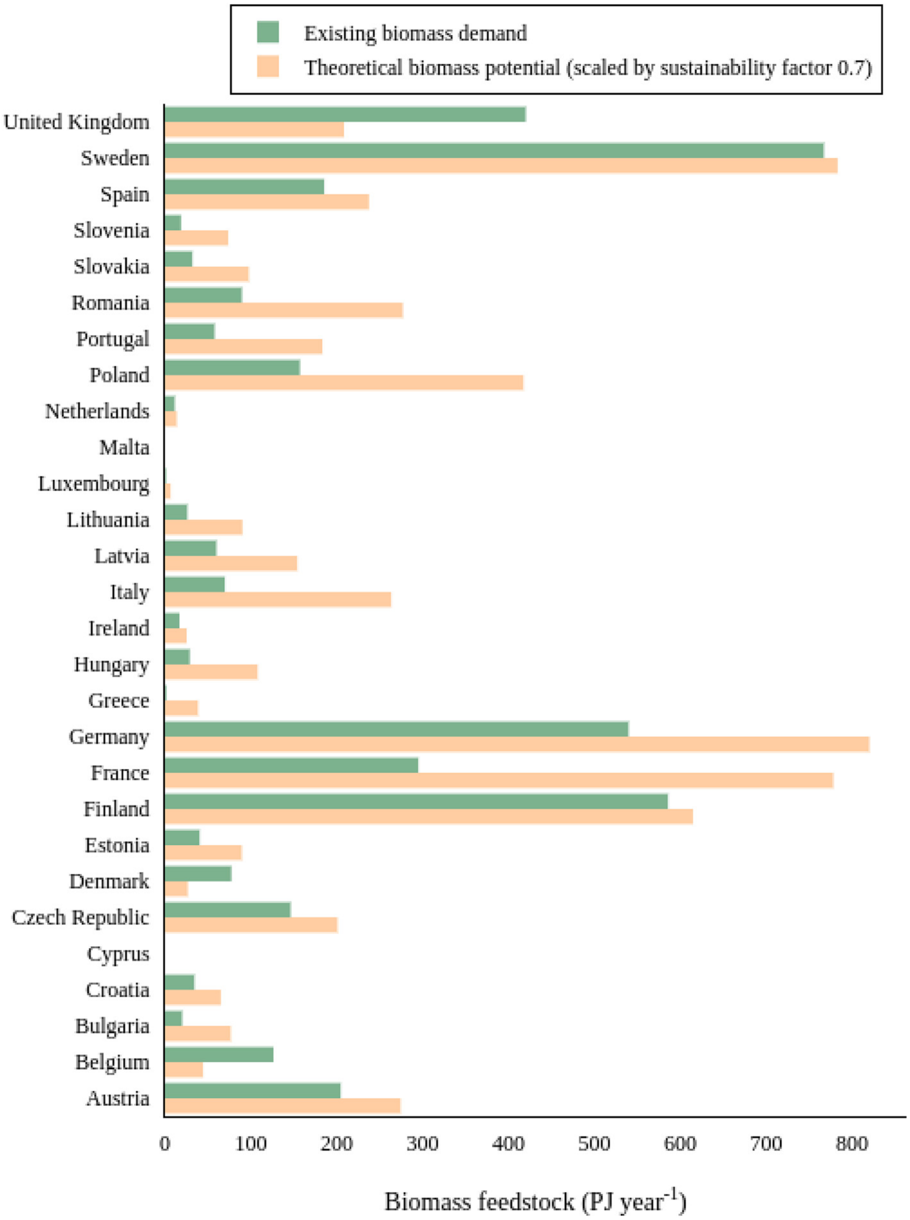


Fig. 5. Comparison of the considered biomass supply and existing demand from sawmills, pulp and paper mills, heat and power plants on country level.

conventional use of biomass within the BF-BOF steelmaking route is in the form of charcoal [29], which requires upgrading using pyrolysis process. Certain studies [21,30] also considered PCI substitution by biomass in the form of wood pellets and torrefied fuel, or by hydrochar produced via HTC from various organic waste-based feedstocks [18]. All of those fuels, however, allow much smaller substitution possibility, as Table 1 shows.

2.2. *BeWhere Europe for iron and steel*

The *BeWhere Europe* model development, in the present work, for integrated iron and steel plants followed its previous grid-based structure, objective function and constraints. In detail, the objective of the model is to minimise the cost of the studied system. This cost is defined as

$$TotCost + TotEmissions \times CarbonPrice,$$

where *TotCost* is the total cost of the system in M€, *TotEmissions* is the CO_2 emissions from fossil fuel use within integrated steel plants in Mt and *CarbonPrice* is the CO_2 price[1] in € t^{-1}. The total cost *TotCost* includes:

- cost of feedstock and its transport,
- cost of biomass upgrading,
- cost of fossil-based reducing agents used within the iron and steel plants, including a constant price for its transport to the plants.

The core of the model is described in detail in the work done by Leduc [32] and Wetterlund [33]. The model is developed in the commercial software GAMS [34], uses a CPLEX solver and the studied problem is expressed via Mixed Integer Linear Programming (MILP).

The variety of feedstock, bio-products and coal substitution opportunities within integrated steel plants required a structural change of

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[1] The present authors report the carbon price based on the carbon dioxide mass equivalent throughout the text. In order to calculate the actual carbon price, the reader must increase the value by the ratio of 3.67, i.e. the molecular mass of carbon dioxide divided by the atomic mass of carbon.

Table 4

Heating values and costs of the considered bio-based fuels. Values were scaled for each country based its Purchasing Power Parity [41], where the listed value in this table is taken as the EU-28 base value.

Bio-product:	Commercialised technologies		Pilot-scale technologies	
	Charcoal	Wood pellets	Hydrochar	Torrefied fuel
Upgrading process:	Slow pyrolysis	Pelletisation	HTC	Torrefaction
LHV (MJkg^{-1}) [47]:	31.6	19.1	22.4 [18]	21.6
Energy retention efficiency:	0.65 [48]	1	0.6 - averaged [49]	0.9
Investment cost (€ t^{-1}):	72.6 [50]	39.1 [51]	71.4 [40]	55.2 [51]
Operation and Maintenance (€ t^{-1}year^{-1}):[a]	3.63	1.95	3.57 [18]	2.76
Average cost of the final bio-product (€ t^{-1}):[b]	255	111	120	147

[a] Estimated as 5% of the investment cost.

[b] Calculated from data within the model.

the *BeWhere Europe* model. The new structure contains a linear flow of raw materials (RM_i, $i \in \{1,...,14\}$), upgrading technologies ($Tech_j$, $j \in \{1,...,7\}$), bio-based products (BP_k, $k \in \{1,...,7\}$) to meet the final demand (D_m, $m \in \{1,...,6\}$) for all industries, and their full list is given in Table 2. For industries that in the previous model did not require any upgrading technology (e.g. pulp and paper mills), an artificial technology – where input is the same as output – was created to follow the structure of the model. The schematic of modified model is shown in Fig. 2.

Due to the variety of technical restrictions associated with the use of different bio-products within the integrated steel plants, specific-steel industry constraints and relationships had to be defined within the *BeWhere Europe* model. In detail, rather than one fuel input, the modified model considers fossil fuels use and their corresponding substitution as three different coal-based fuels: coking coal, coke (including coke breeze) and PCI, where their corresponding limitations for the specific bio-product substitution have been listed in Table 1. In addition, as coke consumption comes from the coking coal input, the model ensures that the substitution happens either for coke or coking coal, as consideration of both would cause double counting of the off-set emissions as well as of the energy use. Detailed description of the model development for the steel industry is provided in the supplementary material.

2.3. Input data

2.3.1. Spatial input

The area across the EU-28 countries was aggregated according to a grid of 40 km × 40 km resolution. Each grid point contains information about the type and amount of biomass available as well as the demand for specific bio-products from each industry. In total, 14 types of bio-based feedstock were considered. Ten of those can be classified as conventional woody biomass (stem wood and logging residues from thinning and final felling, and stumps from final felling, for conifer and non-conifer wood) giving a total theoretical potential within EU in 2020 of 8.53 EJ year^{-1}, as sourced from the S2BIOM project [35]. In order to account for the sustainability aspects, the potential for each woody biomass feedstock was scaled by a factor of 0.7. The other four feedstock types were newly included waste types (green waste, industrial food waste, municipal organic waste and common organic sludges), collected from the Eurostat database [36].

The physical and chemical properties for the waste-based feedstock used for the conversion are summarised in Table 3. The spatial distribution of woody biomass and waste in EU-28 is then presented in Fig. 3. Details of the input feedstock data for each country – availability and cost – can be found in the supplementary material.

Feedstock was able to be transported within the country of origin as well as imported to other EU-28 countries. The transportation cost was considered independently for each type of feedstock, same as in the previous studies [26]. Maximum transport distance of 100 km and no trade opportunities between countries were assumed for the waste-based materials, to consider only local use of such feedstock. As a result, the transport costs for the newly added waste-based materials were rather considered as directly proportional to the distance, i.e. 0.10 € t^{-1}km^{-1} for solid waste [42] and 0.34 € t^{-1}km^{-1} for sludge [43] and scaled based on the Purchasing Power Parity [41] within the EU-28, taking the EU-28 average value as a base.

Spatial input also considered data on existing biomass demand for raw material. In total, annual biomass demand of 1.41 EJ for pulp and paper mills [44], 1.03 EJ for heat and power producing plants [45] and 1.58 EJ for sawmills [46], split across the corresponding locations, had to be met before allocating biomass to any of the steel plants. The spatial locations of the 30 currently operating BF-BOF integrated steel plants in EU-28 were also considered explicitly. The existing biomass demand and the location of each integrated steel plant are plotted in Fig. 4.

The supplementary material provides further details regarding the split of biomass demand by each industry. Fig. 5 provides an aggregated comparison of the woody-biomass supply and the existing woody-biomass demand, per country.

2.3.2. Technical input

The work considered substitution of coking coal, coke breeze, nut

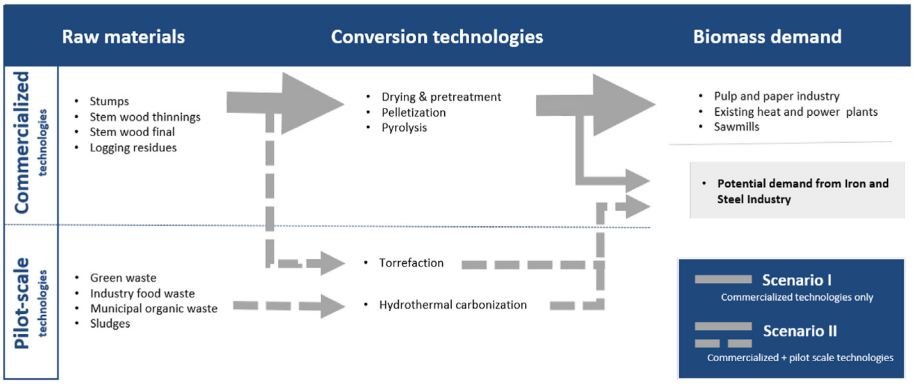


Fig. 6. Scenario construction based on commercialised and pilot-scale technologies considered within the study.

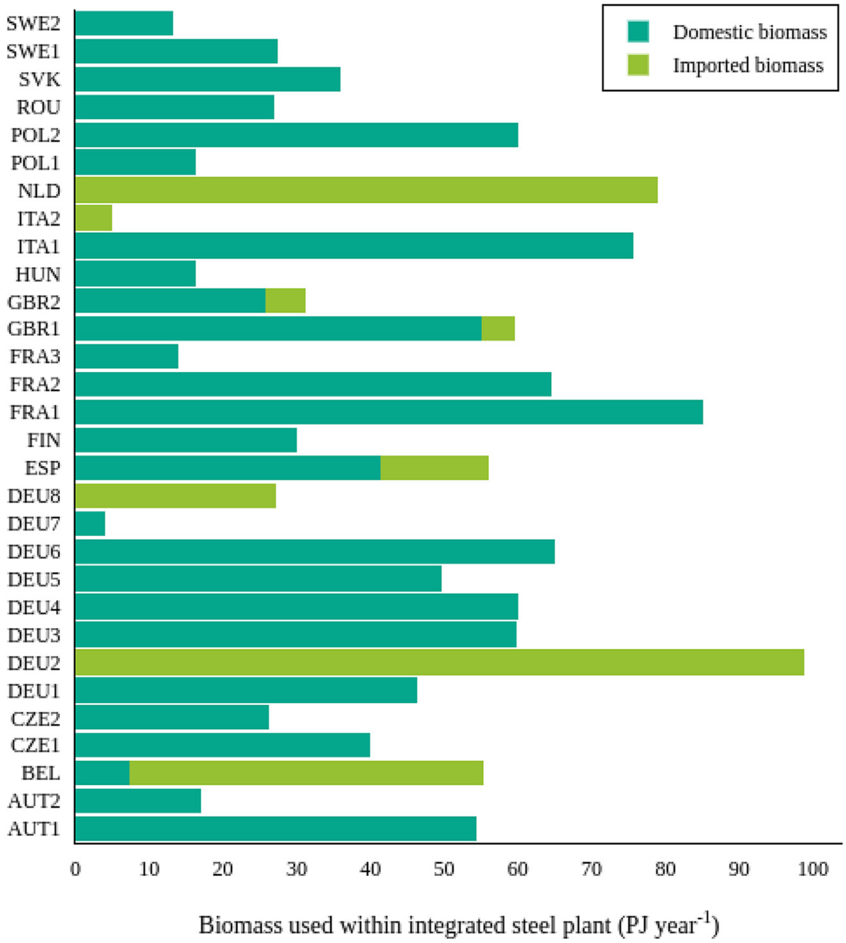


Fig. 7. Optimal sourcing of biomass by each integrated steel plant, when biomass use is maximised.

coke and PCI by charcoal, wood pellets, hydrochar and torrefied fuel, based on substitution possibilities listed in Table 1. Production of each bio-product attained costs related to feedstock purchase, investments in the technologies as well as costs for their operation and maintenance. As the model is working on energy basis, the amount of produced bio-products was scaled by the corresponding energy retention efficiency value of each process. Table 4 summarises the used input values for the bio-products production. Further details on their calculation can be found in the supplementary material.

2.4. Model assumption

Due to the limited availability of publicly accessible data on existing process units at each integrated steel plant around Europe, a simplified approach was used to estimate the possible site-specific biomass substitution. The study assumed that each of the 30 steel plants contains on-site coke ovens, sinter plant and a blast furnace using PCI. In addition, each of those process units was assumed to operate at the same fossil fuel consumption rate per produced tonne of hot rolled coil, using values defined within the IEAGHG report *Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill)* [31], and as shown in Fig. 1. Maximum demand for biomass by each steel plant was estimated based on the annual blast furnace output [52] and maximum potential substitution listed in Table 1. In reality, production facilities at each integrated steel plant are different. Therefore, the results obtained in this study are to compare biomass supply opportunities across different plants, while the actual opportunities for biomass integration by each plant need to be evaluated individually.

2.5. Scenario construction

2.5.1. Commercialisation of pilot-scale technologies

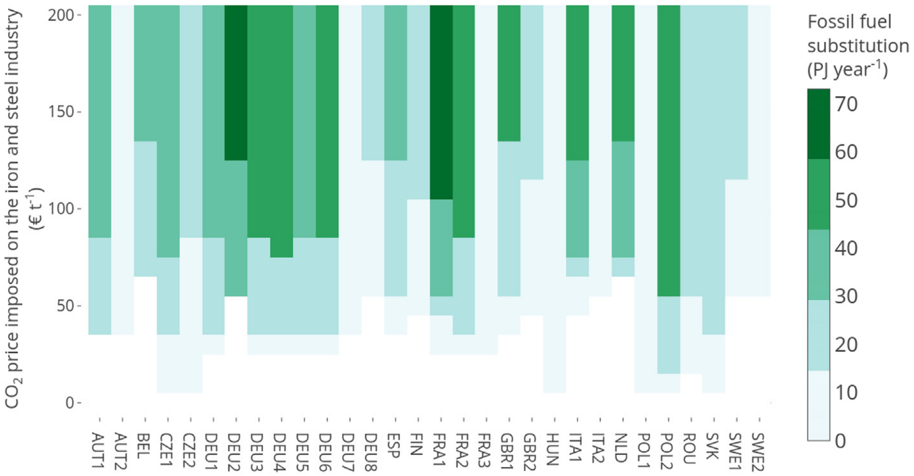
Even though this work included four different bio-based fuels with the potential to substitute coal used within the integrated steel plants, HTC and torrefaction are notably still technologies in pilot-scale, which means their bio-products are not yet on the market. To take this fact into consideration, two different technology scenarios were considered for the study of biomass use across the EU:

- Scenario I – where only commercialised technologies were included (i.e., pyrolysis and pelletisation); and
- Scenario II – where commercialised as well as pilot-scale technologies were considered (i.e., also including torrefaction and HTC).

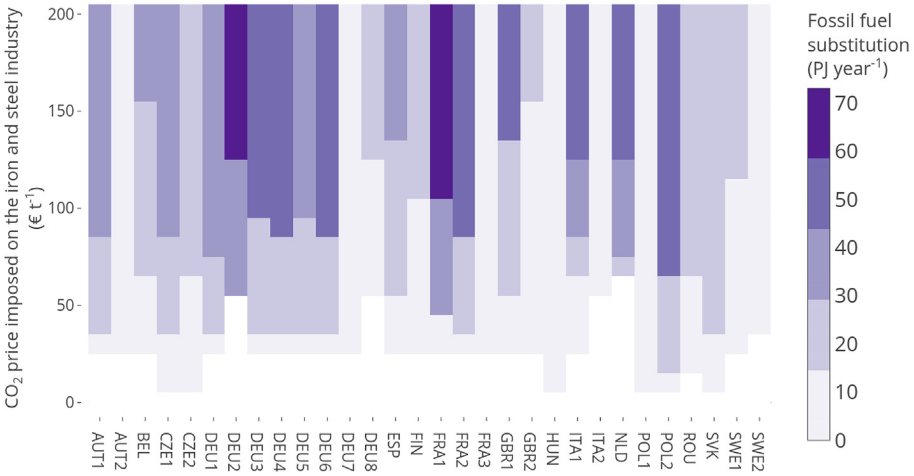
The differences in the scenarios is demonstrated in Fig. 6. The incorporation of this split provides insights to whether support should be given to progressing technologies, as their commercialisation could enhance the opportunities for reducing coal consumption of the iron and steel industry.

2.5.2. Introduction of CO_2 price

The *BeWhere* model finds the cost-optimal utilisation of fossil and biomass resources in Europe based on minimisation of the total cost. Various governmental strategies such as carbon price and ETS can significantly impact the optimal fossil and biomass use, as the monetary cost of the produced fossil-based emissions increases. This study evaluated the impact of the CO_2 price on the feasibility of biomass adoption. CO_2 price values up to 200 € t^{-1} imposed on emissions occurring on-



(a) Scenario I - Commercialised technologies only.



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

Fig. 8. Amount of fossil fuel substituted for each integrated steel plant as CO_2 price increases.

site of the iron and steel plants were considered.

3. Results

3.1. Biomass availability

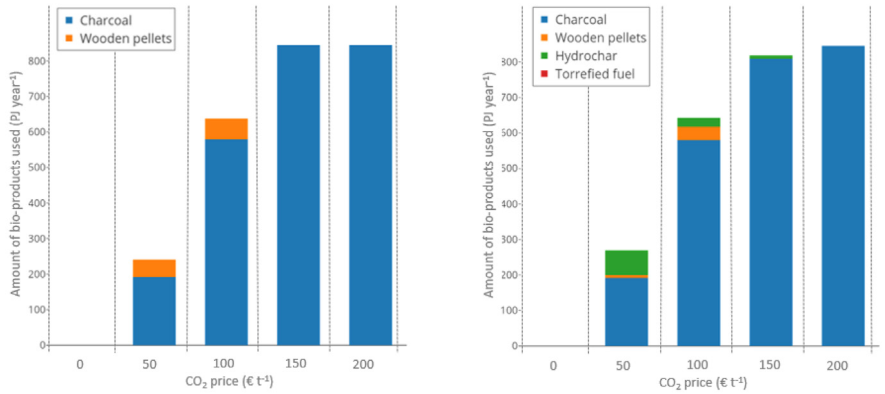
The results show that the biomass potential across the EU-28 countries is sufficient to meet the domestic biomass demand from pulp and paper industry, electricity and power generation plants, sawmills (totalling to 4.01 EJ year^{-1}) as well as the full potential demand for woody-based feedstock by integrated steel plants (1.30 EJ year^{-1}), the value of which limited by the technical feasibility related to fossil fuel substitution by biomass. However, when optimising the whole system based on cost, integrated steel plants in Belgium, Germany, Spain, Great Britain, Italy and Netherlands would heavily rely on imported biomass from other EU countries, as can be observed from Fig. 7.

Despite the surplus of biomass resources across the EU-28 countries, the integrated steel plants will be competing for the available biomass resources against each other as well as against already existing biomass consumers. Fig. 8a and b shows the resulting fossil fuel substitution for each integrated steel plant, at increasing levels of the CO_2 price, for the two considered technology scenarios. As the figure shows, each plant reaches the maximum substitution level at a different CO_2 price, even though the cost of substituted fossil fuels was considered the same across all plants. For example, the French plant FRA2 reaches its maximum substitution at CO_2 price of 90 € t^{-1} while FRA1 would need a CO_2 price of 110 € t^{-1} to reach its maximum substitution. Similarly, the CO_2 price required for initial fossil fuel substitution can also be observed to differ, as is the case for e.g. the German plants.

The introduction of non-commercialised (pilot-scale technologies), in particular HTC technology, would favour fossil fuel substitution at lower CO_2 prices for most of the plants. Comparing Fig. 8a and b, it can be observed that 11 plants would substitute fossil fuels at a lower price when HTC and additional waste-based feedstock is available. However, Fig. 9 demonstrates that even though HTC can support initial substitution, charcoal will still be the most-commonly used bio-product.

3.2. CO_2 emission reduction potential

Emission reduction at different levels of CO_2 price is presented in Fig. 10. As shown, substitution of fossil fuels by bio-based fuels, in amounts close to the top end of the technical feasibility, has the potential to be a significant emission reduction strategy for the European integrated steel plants, if carbon neutrality of the bio-based fuels is



(a) Scenario I - Commercialised technologies only.

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

Fig. 9. Fossil fuel substitution across integrated steel plants split by bio-based fuels.

assumed. The maximum CO_2 emission reduction of 91 Mt can be achieved, which is equivalent to 42% of the CO_2 emissions occurring from coal use by the iron and steel sector in Europe. However, such maximum bioenergy use would occur at scenarios with very high CO_2 price, equal to or greater than 140 € t^{-1}. Conversely, emission reduction of 20% would be economically feasible already at around 60 € t^{-1}. The results thus demonstrate the need of high CO_2 price in order to achieve any significant bio-product integration, otherwise very limited opportunities for CO_2 emission reduction can occur.

Pilot scale technologies would not enhance the maximum emission reduction potential using biomass. However, in particular HTC could slightly increase the opportunities for bioenergy integration at CO_2 prices up to 70 € t^{-1}. This increase is equivalent to an additional annual CO_2 reduction of 1 Mt. The use of hydrochar and wood pellets would be expected to also peak at CO_2 price 70 € t^{-1}. From 80 € t^{-1}, the use of higher quality bio-product in the form of charcoal would be favourable as it allows greater substitution possibilities. Torrefied fuel did not present any additional opportunities for emission reduction within this study.

3.3. Additional costs

Integration of biomass, with the aim to reduce CO_2 emissions would be economically feasible only after imposing a relatively high CO_2 price, which would in turn significantly impact the production cost of steel. For example, initial integration of biomass would start at hot rolled coil production cost of 450 € t^{-1}, which is 5% higher than the base case scenario, the value of which was defined from the IEAGHG report [31]. A 20% fossil fuel substitution would result in a production price of hot rolled coil of 538 € t^{-1}, which is equivalent to a 25% increase. Fig. 11 demonstrates the sensitivity of production costs on the CO_2 price. Overall, the maximum 42% emission reduction using biomass would result in a minimal steel production cost increase by 213 € t^{-1}, roughly 50% cost increase.

The new demand for biomass from integrated steel plants would also influence the costs related to feedstock supply for existing industries. Fig. 12 demonstrates a gradual increase of biomass supply cost for existing industries up to 5.6% as a result of the additional competition for woody feedstock from integrated steel plants. Scenario II would result in slightly lower cost increase when compared to Scenario

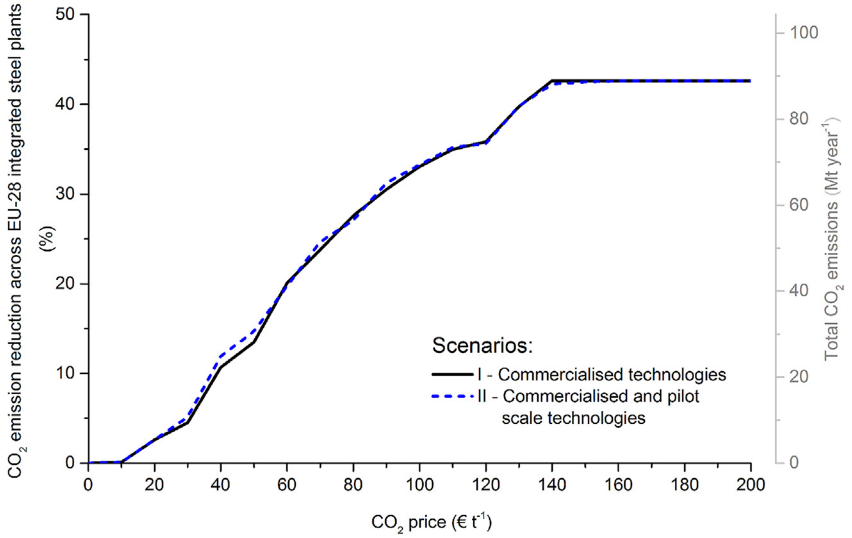


Fig. 10. Total emission reduction across European integrated steel plants at different CO_2 price values. Non-gradual increase indicates the corresponding opportunities at the given CO_2 price that were identified from the modelling.

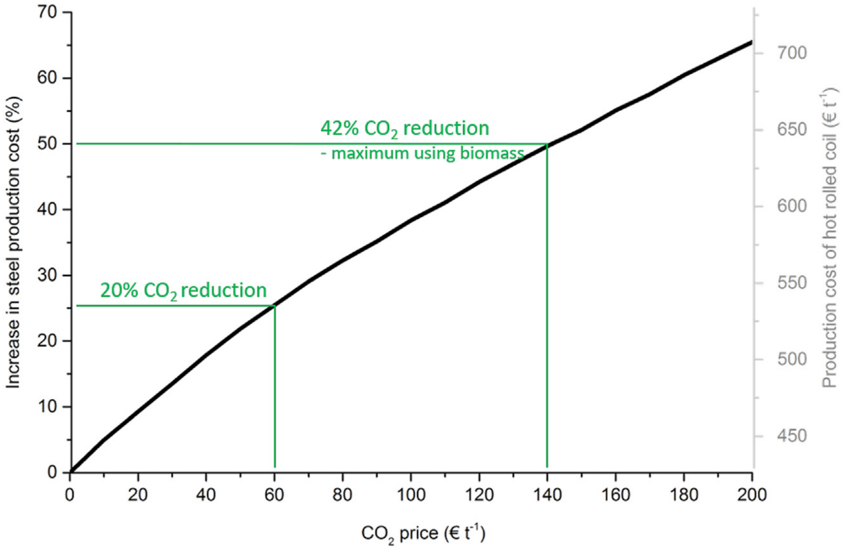


Fig. 11. Change of production cost of hot rolled coil with increasing CO_2 price.

I, which is due to the possibility for integrated steel plants to use bioproducts from waste-based feedstock, hence reducing the woody-biomass demand by steel plants.

4. Discussion

4.1. Feasibility of bioenergy deployment within European integrated steel plants

The work has evaluated the techno-economic potential to use European biomass resources to substitute coal used for ironmaking, while still ensuring the supply for the existing biomass users is preserved. The input woody feedstock values considered in this study (5.97 EJ $year^{-1}$ ≡ 681 hm^3, after re-scaling the initial values by sustainability factor 0.7) were very close to raw feedstock potential at 2020 medium mobilisation scenario value 678 hm^3 given in Ref. [53]. Estimates by Mantau et al. [53] for demand by sawmills (219 hm^3), heat and power plants (242 hm^3), and pulp and paper industry (168 hm^3) at the 2020 IPCC scenario also correspond to data used by this work for the annual demand of the specified industries (1.58 EJ ≡ 216 hm^3, 1.03 EJ ≡ 140.7 hm^3 and 1.41 EJ ≡ 193 hm^3, respectively). Note, the units used by Mantau et al. [53] have been corrected in the data shown above. When comparing the results for the Finnish integrated steel plant obtained in this work, they are largely found to agree with a previous country specific study on Finland only [20]. Suopajarvi and Fabritius [20] estimated breakeven CO_2 price for metallurgical coke substitution already at 16 € t^{-1} and for PCI at 50 € t^{-1}, while this work resulted in initial substitution at 50 € t^{-1}, which can be due to the lower metallurgical coke price considered in this study. Findings of sufficient biomass availability in this paper also agreed with a previous country specific study for Sweden [54]. The compliance of the model values and previous literature strengths conclusions on the given biomass potential.

However, even though this study has identified relatively large amounts of available biomass, it does not indicate that this will be the case also at the time of its potential implementation. First, the study has not considered the planned as well as potential increase of biomass use in the other sectors, for production of electricity, heat and transport fuels, which are also aiming to use bioenergy to meet their emission reduction targets. Second, meeting the economic potential does not mean that all sustainability criteria are met. Despite considering only 70% of the theoretical potential for estimation of the economic potential, the data on biomass availability considered in this study does not necessarily reflect the amount of biomass which use would not conflict with other environmental quality objectives, like forest protection and preservation of biodiversity, as has been discussed e.g. for Swedish conditions by de Jong et al. [55].

In addition, using up to 1.30 EJ of biomass, out of the full theoretical potential of 8.53 EJ only for the purpose of iron and steelmaking is recognisably a significant share. In other words, 15% of the theoretical biomass potential would have to be set aside to meet biomass demand by only 30 plants across the whole of Europe. This could negatively impact the European biomass market and also significantly limit the opportunities for bioenergy deployment and associated CO_2 emission reduction in other industries or sectors. Therefore, even though this work has identified sufficient biomass availability, further work is required to ensure that the solution supports strategic biomass use in Europe and all potential end uses are sustainable in the long run.

Lower impact on existing biomass market was observed when the iron and steel plants had the option to also use the HTC technology, which uses waste-based feedstock. This study, however, did not consider the high competition for waste from e.g. waste incineration, biogas production and other energy-from-waste plants, which all have to meet their capacities. On the other hand, use of waste-based feedstock in steel plants would be particularly appealing in locations where waste is mainly landfilled, specifically for the ones which have not achieved reduction of biodegradable waste to the amounts set by the EU Landfill Directive (1991/31/EC) [56]. Landfilling biodegradable waste produces large amounts of methane, the main component of landfill gas, which has a high global warming potential (GWP). Lee et al. [57] estimated production of CO_2eq emissions from dry food waste as 2.71 t t^{-1}, which can be reduced to 1.52 t t^{-1} if the landfill gas is used for electricity production. Utilising food waste for hydrochar used in ironmaking can offset those CO_2 emissions from dry food waste by an additional 1.02 t t^{-1}.[2]

Lastly, the economic viability of bioenergy deployment across the

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[2] Obtained from using CO_2 emission factor of PCI coal of 3.19 kg kg^{-1} and heating value of 33.4 MJ kg^{-1} [31], heating value of dry food waste of 19.5 MJ kg^{-1} [58], 0.6 as the energy retention efficiency of the HTC process listed in Table 4 and 1.1 is the substitution equivalency of hydrochar and PCI [18].

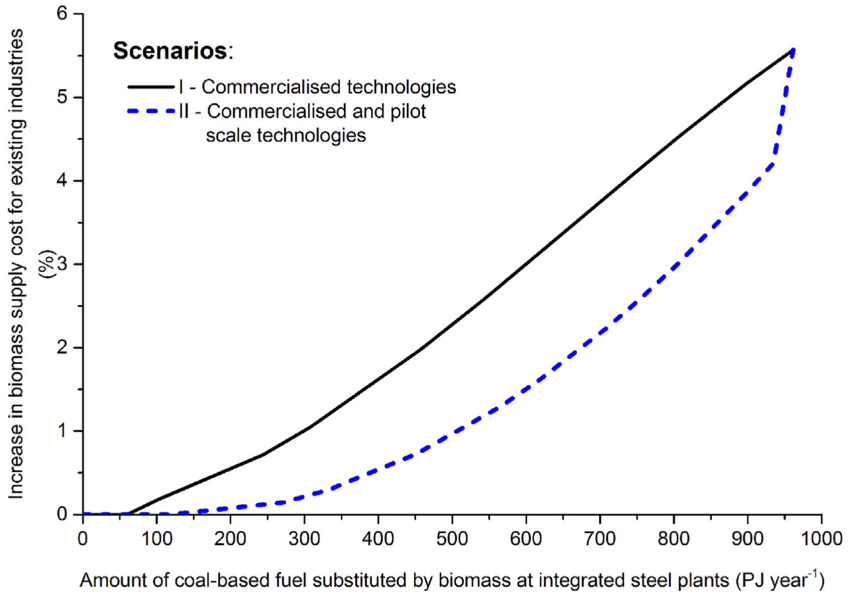

Fig. 12. Impact of bioenergy utilisation within integrated steel plants (influenced by varying CO_2 price) on feedstock supply costs of existing biomass industries.

European integrated steel plants constitutes a significant barrier. An increased production of bio-products resulting from a new demand by the steel industry might decrease the bio-product production costs, due to technological learning and technology scale-up. However, even with decreased production costs, the bio-products are unlikely to become cost-competitive to fossil fuels within the foreseeable future.

4.2. Roadmap for reducing environmental impact of the iron and steel production

Biomass integration would significantly increase the production cost of steel in Europe. As the results show, the maximum 42% attainable fossil fuel substitution by biomass would increase the steel production cost by a minimum of 50%. Indeed, iron and steel production is highly CO_2 intensive and, depending on the political development, the sector could be forced to internalise a larger share of their environmental impact, compared to today. However, steel is also an internationally traded material so any additional costs (either due to emissions or to purchasing alternative fuels) could significantly impact its competitiveness, which is already struggling against cheap steel imports from countries outside Europe, for instance China.

Even though some studies have argued that the CO_2 price, presented across Europe as the EU-ETS, should not have a major impact on the productivity and competitiveness of this industry [59], the EU-ETS still might not be the best way to reduce fossil fuels use by its substitution by biomass in this sector. In addition, Schwaiger et al. [60] also pointed out that the price fluctuations of the allowances do not encourage long term investments into bioenergy technologies in general. Further, the results demonstrated a large difference in the introduction and use of bio-products between countries as well as between individual plants. Therefore, alternative policy instruments, such as subsidies or tax relief, might be better incentives. However, those types of governmental strategies may conflict with the current EU policy direction, where certain policy instruments can be considered as state aid [61], which risks leading to market distortions. Therefore any state aids are strictly regulated [62].

In addition, the maximum emission reduction of 42% indicates that bioenergy should not be relied upon in isolation as the sole long-term emission reduction strategy for the iron and steel making in Europe. Instead, bioenergy needs to be integrated with other strategies. For example, its co-application with CCS (known as BECCS), which on its own can avoid up to 60% CO_2 emissions [31], could theoretically achieve carbon neutrality of European iron and steel making without needing to significantly change the existing process plants. However, the CCS application also has high CO_2 avoidance cost starting from 60 € t^{-1} [31], which would add further costs to the steel production in Europe, with associated effects on its competitiveness on the global market.

Biomass, in the form of charcoal, has been also tested for HIsarna (direct reduced iron process, using smelting reduction) to partially substitute coal. HIsarna is expected to be able to reduce CO_2 emissions by 20%, which can be increased to up to 80% with the addition of CCS [63]. With additional bioenergy utilisation, the emissions in both cases can be further reduced. HIsarna is, however, still in the demo-pilot scale state and its full-scale application is undetermined yet [64].

5. Conclusion

This study evaluated the viability of bioenergy usage within integrated steel plants around Europe, from the resource, CO_2 emission and economic perspective, in order to increase the knowledge regarding the potential role of bioenergy in European integrated steel plants. The results demonstrated that sufficient biomass resources exist to meet the maximum technical biomass demand by all steel plants, but that steel plants in Belgium, Germany, Spain, Great Britain, Italy and Netherlands would be highly reliant on cross-border biomass trading. On the other hand, deployment of biomass within integrated steel plants would require a large share of the total biomass potential in the EU, which would in turn significantly impact the potential for biomass deployment in other sectors.

Pilot scale technologies, particularly HTC, would not enhance the maximum potential emission reduction, and would only slightly contribute to the total fossil fuel use reduction across the integrated steel plants. This case would be even when waste-based feedstock is transported more than 100 km, as use of such feedstock is limited by technical rather than supply aspects. On the other hand, the possibility to use waste would broaden the feedstock base for the iron and steel plants and thus to some extent reduce the impact of increased biomass competition for existing users. In addition, using bio-degradable waste within iron and steel making could, apart from offsetting the use of coal and the corresponding emissions, also offset emissions resulting from landfill gas production, if the waste would have otherwise been landfilled.

In total, bioenergy can reduce the CO_2 emissions resulting from coal use in iron and steel making by up to 42%. The maximum achievable emission reduction is capped by technical limitations, not biomass availability. However, such emission reduction would require a CO_2 price of 140 € t^{-1}, while a 20% emission reduction could be attained already at a CO_2 price of 60 € t^{-1}. When no CO_2 price is imposed, no substitution can be expected. It is concluded that the main barriers for biomass deployment in Europe are related to supply costs of the bio-products, not necessarily biomass availability. The EU-ETS can contribute to the introduction of biomass in steel making, but this would significantly impact the production cost of steel in Europe. Therefore the EU-ETS might not be the best tool for bioenergy integration, and other measures such as subsidies or tax relief might need to be considered to also retain competitiveness of the European steel products on the global market. This could, however, risk conflicting with the current EU policy direction.

Acknowledgements

H. Mandova would like to thank the EPSRC CDT in Bioenergy [Grant Ref: EP/L014912/1] for her studentship and acknowledge that this research was developed in the Young Scientists Summer Program (YSSP) at the International Institute for Systems Analysis (IIASA), Laxenburg (Austria) to which the author would like to thank for the opportunity. The financial support by the Swedish Research Council ‘'Formas” (dnr. 213-2014-184) for IIASA, from VINNOVA (dnr: 2017-01327) for MEFOS and from the Swedish Energy Agency and Bio4Energy are also acknowledged. In addition, the authors would like to thank Dr. Peter Hodgson from Tata Steel for helpful discussions.

All data generated by this study are included in either the paper or the supplementary material provided. Where third party datasets have been employed, these are referenced.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2018.04.021.

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