Supplementary material

For manuscript entitled:

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

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Model

BeWhere model

The work uses the techno-economic *BeWhere-EU* model (IIASA, 2015) and follows us on its previous development for specific study on the iron and steel industry in Europe (Mandova et al., 2018). The model is described via Mixed Integer Linear Programming (MILP) and solved using CPLEX as solver in the commercial software GAMS (McCarl et al., 2016). The key idea behind the model is to divide the studied geographic region into equal size grid cells, in this case 40km X 40km, where each grid cell is assigned an ID number. Information on the amount and type of biomass supply, biomass demand as well as study specific information (in this case, information about the size, annual emissions and energy demand of the iron and steel plant) are stored for the corresponding grid ID. In addition, transport distances between each grid point are also inputted in the model. The optimal solution is then obtained based on matching supply and demand, with an aim to minimise the total system cost. General aspects of the model can be found in the work by Leduc (2009) and Wetterlund et al. (2012). This report focuses on specific information, model adjustments and input values used for the work "Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage".

Model constraints

Model constraints allow to introduce restrictions on different aspects within the studied system that would usually happen in the real life and therefore should be accounted for. The key areas considered are:

- *Biomass availability* – restriction that only 70% of the theoretical potential could be used in order to represent sustainability consideration in the work;
- *Technical limitations using biomass* – taking into account that not all fossil-based fuels can be substituted by bio-based fuels;
- *Biomass trade* – Biomass trade (within Europe or for importing biomass from outside of Europe) is possible only at specific locations;
- Amount of CO_2 technically possible to be captured – accounting maximum CO_2 capture efficiency due to the imposed technology.

Each constraint is discussed further in the corresponding section below.

Modelling approach

The complexity of the problem and requirement to undertake various calculations require interlinkage of multiple input data, constraints and three modules, as Figure 1 shows. The first calculation requires estimation of the available biomass, using the basic *BeWhere – EU* module. The second step is to define the CO_2 transport network and the cost for CO_2 transport and storage for each plant. This is done using the *CO_2 TranStorage* module. The outputs of those two modules are then used as inputs for the main module, referred to here as *BeWhere – EU – Iron & Steel*.

Area of study

The focus of the study is on the EU-28 countries region (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and United Kingdom).

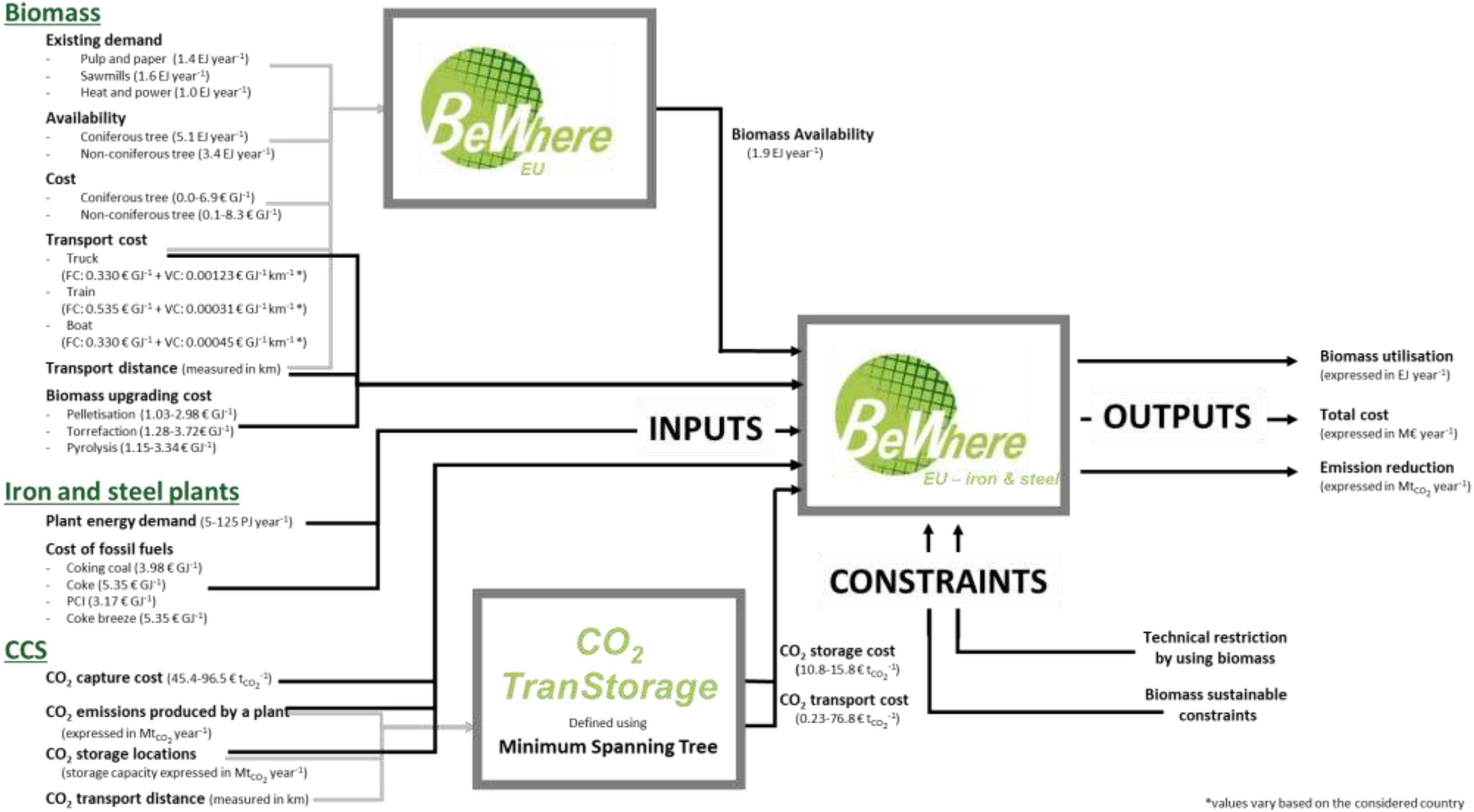

Figure 1: Summary of inputs, outputs and constraints considered for this study. Examples of the data given above. (FC – Fixed cost, VC – Variable cost)

Biomass

Feedstock

In total, 10 different types of woody based feedstock are considered. The feedstock is classified either as conifer or non-connifer trees, and further defined as either:

- Stumps;
- Stemwood from final fellings;
- Stemwood from thinnings;
- Logging residues from final fellings;
- Logging residues from thinnings.

The feedstock data is obtained from the S2Biom project and its estimates of theoretical potential in 2020 (Dees et al., 2017). The density of each type of feedstock is listed in Table 1. In total 8.53 EJ is estimated as available, the split based on countries and the associated cost for each are provided in Table 3 and 4. However, as mentioned above, only 70% of the available biomass is considered in order to account for the sustainability constraints during this study.

Table 1: Energy density of the considered feedstock. Values obtained from the S2Biom project (Dees et al., 2017).

	Nonconifer trees					Conifer trees				
	Stumps from final fellings	Stemwood from final fellings	Stemwood from thinnings	Logging residues from final fellings	Logging residues from thinnings	Stumps from final fellings	Stemwood from final fellings	Stemwood from thinnings	Logging residues from final fellings	Logging residues from thinnings
Kg m^{-3}	542	549	542	542	542	415	420	415	415	415
MJ kg^{-1}	18.6	19	19	18.7	18.7	18.6	19.3	19.2	19.2	19.2
MJ m^{-3}	10,081	10,431	10,298	10,135	10,135	7,719	8,106	7,968	7,968	7,968
GJ m^{-3}	10.1	10.4	10.3	10.1	10.1	7.7	8.1	8.0	8.0	8.0

Biomass trade

Trading opportunities between countries is considered at specific trading points. For trading within the EU-28 countries, no penalty for importing biomass is accounted for, only the corresponding feedstock and transport. Importing biomass from outside EU-28 countries is also possible at one of seven specified locations (marked in Figure 3 in the main article) at a cost 20% higher than average biomass cost within the country the harbour is located at (Wood Chain Manager, n.d.). Further details on the trading aspects incorporated within the BeWhere model can be found in work by Wetterlund (2010) and Wetterlund et al. (2012).

Transport

Transport distance between each grid is calculated using the network analysis tool within ArcGIS. Three different transport types are considered: truck (maximum distance 250km), train (maximum distance 200) or boat (unlimited distance), following work on biomass transport cost by Börjesson and Gustavsson (1996). The cost is estimated based on the amount of energy transported and the distance between supply and demand. The specific fixed cost and variable cost values are country specific, scaled using fuel cost within the corresponding country. Equation 1 demonstrates the transport cost calculation, where average values for fixed and variable cost can be found it Table 2.

$$Transport\ cost = Fixed\ cost + Variable\ cost\ \times Transported\ distance \tag{1}$$

Table 2: Average fixed and variable cost estimates for transport type.

	Fixed cost € GJ^{-1}	Variable cost € GJ^{-1} km^{-1}
Truck	0.32973	0.00123
Train	0.53514	0.00031
Boat	0.32973	0.00045

Table 3: Feedstock availability, expressed as raw biomass.

	Nonconifer trees (PJ $year^{-1}$)					Conifer trees (PJ $year^{-1}$)				
	Stumps from final fellings	Stemwood from final fellings	Stemwood from thinnings	Logging residues from final fellings	Logging residues from thinnings	Stumps from final fellings	Stemwood from final fellings	Stemwood from thinnings	Logging residues from final fellings	Logging residues from thinnings
Austria	5.7	16.0	28.5	4.7	9.7	60.8	146.4	50.5	48.5	21.1
Belgium	2.5	9.8	7.6	2.5	2.2	5.4	17.8	7.0	5.2	3.6
Bulgaria	9.6	27.5	11.2	13.6	5.7	3.2	7.6	15.2	3.6	12.1
Croatia	8.9	40.6	19.7	6.7	3.6	2.2	6.2	2.8	1.5	0.9
Cyprus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Czech Republic	9.3	36.5	23.1	9.7	7.4	25.8	79.0	46.6	29.0	20.6
Denmark	1.0	3.5	4.1	0.9	1.2	3.1	11.8	5.6	3.4	3.3
Estonia	7.3	47.5	11.2	6.9	1.7	6.0	27.5	11.5	5.6	2.6
Finland	15.0	25.1	25.7	10.8	12.1	127.2	322.6	175.9	101.0	62.8
France	76.0	288.7	146.8	74.5	42.4	62.3	175.8	138.4	50.3	56.7
Germany	56.0	205.2	129.6	56.1	39.9	94.8	263.0	158.2	92.3	76.6
Greece	2.5	11.6	10.7	3.0	2.8	2.2	7.8	7.8	3.3	3.5
Hungary	18.3	59.1	26.0	19.6	9.1	3.0	8.2	5.1	2.5	3.3
Ireland	1.7	8.7	0.7	1.3	0.1	3.0	10.4	6.3	1.6	2.1
Italy	59.9	154.8	31.4	39.7	9.7	11.1	27.3	25.1	8.8	8.6
Latvia	18.6	62.7	12.8	20.8	4.4	17.6	52.8	11.7	14.9	3.9
Lithuania	8.8	25.2	9.9	7.0	2.8	13.0	32.8	11.7	12.3	5.1
Luxembourg	0.9	3.2	0.6	0.8	0.2	0.4	1.2	1.2	0.4	0.5
Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Netherlands	0.8	3.7	4.0	0.5	0.7	1.2	3.3	3.5	0.7	1.3
Poland	21.9	82.9	27.2	16.2	5.9	77.0	206.8	65.4	63.0	30.0
Portugal	49.7	94.0	0.9	26.5	0.5	23.8	39.4	4.4	20.6	2.3
Romania	28.3	107.5	69.8	28.5	19.8	17.6	59.9	36.2	15.6	12.5
Slovakia	8.2	25.9	20.4	10.1	8.7	10.4	29.0	10.5	11.1	5.2
Slovenia	5.5	22.0	9.1	4.5	2.2	12.0	30.2	8.9	7.8	3.1
Spain	27.9	43.1	15.0	18.0	6.0	44.5	80.8	49.2	31.8	23.1
Sweden	28.7	57.5	48.3	14.0	13.4	143.3	372.6	248.1	105.3	87.6
United Kingdom	20.9	68.4	26.8	20.9	8.6	18.0	88.4	25.6	13.7	6.7

Table 4: Feedstock cost, expressed as raw biomass.

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

Existing biomass demand

Pulp and paper plants, sawmills as well as plants producing heat and power are here considered as the main industries, against which the iron and steel would be competing for the biomass resources. The existing annual biomass demand from those industries is summarised in Table 5. To avoid modelling results where biomass supply cost for the existing industry will increase in order to supply cheap biomass to the iron and steel plants, existing demand is met first, before any biomass is considered as available for the iron and steel consumption. This calculation is done within the *BeWhere-EU* module and its outputs are used in the main *BeWhere – EU – Iron & Steel* module. Consideration of the future demand within a spatial explicit approach, where specific plants are individually considered, is difficult due to uncertainty in future progress of each plant. At the same time, there is limited data availability of the future biomass demand of each industry in each of the EU-28 countries too. Therefore, this work does not consider future demand, and focuses its analysis on the current situation.

Table 5: Annual biomass demand considered in this study for sawmills, pulp and paper mills and heat and power plants.

	Pulp and paper (PJ year^{-1})	Sawmills (PJ year^{-1})	Heat and power (PJ year^{-1})
Austria	43.3	134.5	26.8
Belgium	22.1	24.1	80.2
Bulgaria	4.5	13.7	1.9
Croatia	9.0	23.2	2.1
Cyprus	0.0	0.0	0.0
Czech Republic	80.7	61.5	4.2
Denmark	4.9	5.6	66.7
Estonia	4.6	29.2	6.6
Finland	298.3	166.6	120.9
France	139.6	110.7	44.8
Germany	144.4	323.8	71.7
Greece	0.0	1.6	0.0
Hungary	8.6	7.6	12.7
Ireland	0.0	14.4	2.4
Italy	27.1	21.9	20.8
Latvia	0.0	57.0	3.0
Lithuania	0.0	20.5	5.5
Luxembourg	0.0	1.1	0.1
Malta	0.0	0.0	0.0
Netherlands	0.0	2.7	8.8
Poland	61.9	71.7	23.6
Portugal	32.2	16.7	9.0
Romania	5.5	81.8	2.3
Slovakia	8.5	23.1	0.3
Slovenia	7.6	10.7	0.4
Spain	124.5	36.5	24.5
Sweden	344.8	262.5	159.7
United Kingdom	39.1	52.6	328.4
	1411.1	**1575.3**	**1027.3**

Pulp and paper

Only stemwood from final fellings and from thinnings of both conifer and nonconifer trees are considered for meeting the pulp and paper demand. The annul biomass demand is obtained from CEPI database (CEPI, 2017). Even though pulp and paper industry uses residues from sawmills to meet the biomass demand, this study omits this fact to consider a higher end of the biomass demand from this industry. The initial values are converted from total pulp to total biomass demand by multiplying by 2 (product of 5 and 0.4). The obtained values are further divided by 10^6 (to get values in Mt) and then multiplied by 18.95 MJ kg^{-1} to obtain conversion to PJ.

Sawmills

Annual biomass demand by sawmills is estimated from sawnwood production (m^3) (FAO, 2016), for which only stemwood from final fellings from conifer and nonconifer trees is considered. To estimate demand of sawlogs, sawnwood is multiplied by 2 (Fonseca and Task Force Members, 2010) and divided by 10^6 to obtain value in hm^3. Demand in PJ $year^{-1}$ is achieved by multiplying this value by 7.3 PJ hm^{-3}.

Heat and power

Demand for biomass from heat and power plants is obtained from Platts database (Platts, 2017), listed as plant output in MW. Conversion to MWh is based on the assumption of annual operation of 6000 hours. Conversion to PJ is achieved by dividing the value by 0.4 (assuming 40% efficiency), then further multiplying by 3.6 and dividing by 10^6 to obtain values in PJ $year^{-1}$.

Upgrading & Bio-products

Three different types of upgrading and the corresponding bio-products are considered: pyrolysis, torrefaction and palletisation. Specific values are scaled using Purchasing Power Parity (European Commission, 2016), taking the initial value as EU-28 average.

Cost of charcoal, from pyrolysis, is estimated from value 112 USD t^{-1} (Norgate and Langberg, 2009), converted using Statista conversion value of USD to EUR as 1.47 in 2008. Pelletisation production cost is defined in literature as 41 EUR t^{-1} (Uslu et al., 2008). Torrefaction production cost as 58 EUR t^{-1} (Uslu et al., 2008). Values initially in EUR t^{-1} are converted to EUR GJ^{-1} using LHV listed in Table 6.

Table 6: Production cost of various bio-products.

		Charcoal	Wood pellets	Torrefied fuel
LHV	GJ t^{-1}	31.64	19.10	21.64
Total production cost	€ t^{-1}	76.19	41.00	58.00
	€ GJ^{-1}	2.41	2.15	2.68

Iron and steel plant

Iron and steelmaking

In total, 30 currently operating integrated steel plants across the EU-28 countries are considered. Based on 2016 data of their blast furnace output, the value is multiplied by 1.116 to achieve an estimate for the liquid steel production (IEAGHG, 2013). To ensure comparability on the country level, the obtained values are further corrected such that national crude steel production equals the crude steel production from oxygen-blown converters in 2016 from World Steel Association report *Steel Statistical Yearbook 2017* (World Steel Association, 2017). Data confidentiality agreement unfortunately does not allow publication of the data on iron and steel production of each plant used within this study.

Coal and electricity demand

In total, four types of coal-based fuels are considered for substitution: coking coal, coke, coke breeze and pulverised coal injected to the bottom of blast furnace (PCI). The work follows on the previous development of the *BeWhere-EU iron & steel* model, described in detail in Mandova et al. (2018) (and the corresponding supplementary material), following description of the reference steel plant given in the IEAGHG report (IEAGHG, 2013). Unlike in the study mentioned in Mandova et al. (2018), this work also considers emissions from natural gas used to generate additional electricity demand not being able to cover by electricity production from the off gases. The CO_2 emission intensity of steel production is considered as 2.090 t_{CO_2} t_{HRC}^{-1}.[1]

Maximum substitution of the four coal-based fuels by bio-products is summarised in Table 7. Substitution is done on energy basis, where wood pellets and torrefied fuel is substituted in 10:11 ratio to account for the lower fuel quality level. However, quality of charcoal as fuel is considered as sufficient to allow 1:1 substitution ratio.

Table 7: Maximum substitution possible for each type of coal-based fuel.

	Amount used (IEAGHG, 2013)	**Wood pellets** (Wang et al., 2015)	**Torrefied fuel** (Wang et al., 2015)	**Charcoal** (Suopajärvi et al., 2017)
Coking coal	524 kg t_{HRC}^{-1}	-	0	10%
Lump coke	352 kg t_{HRC}^{-1}	-	0	45kg t_{HM}^{-1}
Coke breeze	55.6 kg t_{HRC}^{-1}	-	0	100%
PCI	151 kg t_{HRC}^{-1}	20%	22.8%	100%

CCS

CO_2 capture

Based on the IEAGHG report (IEAGHG, 2013), two levels of CO_2 capture rate for post-combustion capture using conventional MEA within an integrated steel plant are considered:

- CASE 1: capture of CO_2 from flue gases of the hot stoves and steam generation plant
- CASE 2: capture of CO_2 from flue gases of the hot stoves, steam generation plant, coke ovens' underfired heaters and lime kilns.

The calculation of CO_2 avoidance cost using CCS in the IEAGHG report (IEAGHG, 2013) is based on the assumption that the flue gases produced during the iron and steel making process, and usually used for electricity generation, are now used within the steam generation plant required for the carbon capture. The required electricity demand by the steel plant would then be met by externally supplying natural gas to the power station on-site. For this study, such assumption would not be viable to apply for all steel plants as some of them (e.g. in Sweden) are not connected to natural gas network. This work hence assumes that the plants will be directly importing electricity rather than natural gas. In detail, the work first calculates the steel production cost without electricity and then substitutes the electricity production cost given within the IEAGHG report by the country specific prices for industries

[1] HM = Hot metal
HRC = Hot rolled coil

with consumption above 70,000 MWh in 2017 (taking the year average) (Eurostat, 2017). This electricity price estimate includes all taxes and levies. As the IEAGHG report (IEAGHG, 2013) presents the cost calculation for 2010, its steel production cost is scaled by factor 1.108 – the inflation factor defined from 01/01/2010 to 1/12/2017 (Fxtop, n.d.). Table 8 and 9 summarise all the undertaken calculations. CO_2 capture cost is hence estimated on the country level rather than plant level.

Table 8: Calculation of steel production cost without electricity component.

CO_2 emissions	Reference	Case 1	Case 2
Direct CO_2 emissions (kg t_{HRC}^{-1})	2090.14	1041.73	827.42
CO_2 emissions avoided (kg t_{HRC}^{-1})		1048.41	1262.72
USD 2010	Reference	Case 1	Case 2
Steel production cost (USD t_{HRC}^{-1})	575.23	652.44	677.7
Electricity kWh t_{HRC}^{-1}	400.1	572.6	621.7
Electricity USD MWh^{-1}	143	95	95
Electricity cost USD t_{HRC}^{-1}	57.21	54.40	59.06
Steel production cost without electricity (USD t_{HRC}^{-1}):	518.02	598.04	618.64
EUR 2010 (1.34 USD = 1 EUR)	Reference	Case 1	Case 2
Steel production cost (EUR t_{HRC}^{-1})	429.28	486.90	505.75
Electricity EUR MWh^{-1}	106.72	70.90	70.90
Electricity cost EUR t_{HRC}^{-1}	42.70	40.59	44.08
Steel production cost without electricity (EUR t_{HRC}^{-1}):	386.58	446.30	461.67
EUR 2017 (Inflation factor 1.1108)	Reference	Case 1	Case 2
Steel production cost (EUR t_{HRC}^{-1})	476.84	540.84	561.78
Electricity EUR MWh^{-1}	118.54	78.75	78.75
Electricity cost EUR t_{HRC}^{-1}	47.43	45.09	48.96
Steel production cost without electricity (EUR t_{HRC}^{-1}):	429.41	495.75	512.82

Table 9: Calculation of CO_2 avoidance cost.

		Electricity cost (EUR t_{HRC}^{-1})		Steel production cost (EUR t_{HRC}-1)		**CO_2 avoidance cost (EUR t_{CO2}^{-1} avoided)**	
Country	Electricity price (EUR kWh^{-1})	Case 1	Case 2	Case 1	Case 2	**Case 1**	**Case 2**
Austria	0.0792	45.35	49.24	541.10	562.06	61.29	67.49
Belgium	0.0718	41.08	44.61	536.83	557.43	57.22	63.82
Czech Republic	0.0782	44.78	48.62	540.53	561.44	60.75	67.00
Finland	0.0633	36.25	39.35	532.00	552.18	52.61	59.66
France	0.0614	35.16	38.17	530.91	551.00	51.57	58.73
Germany	0.1369	78.36	85.08	574.11	597.90	92.78	95.88
Hungary	0.0907	51.91	56.36	547.66	569.18	67.55	73.13
Italy	0.0943	53.97	58.60	549.72	571.42	69.51	74.90
Netherlands	0.0639	36.59	39.73	532.34	552.55	52.94	59.96
Poland	0.0758	43.37	47.09	539.13	559.92	59.41	65.79
Romania	0.0751	43.00	46.69	538.75	559.51	59.05	65.47
Slovakia	0.1108	63.44	68.88	559.19	581.71	78.55	83.05
Spain	0.0870	49.82	54.09	545.57	566.91	65.55	71.33
Sweden	0.0501	28.66	31.12	524.41	543.94	45.37	53.14
United Kingdom	0.1381	79.05	85.83	574.80	598.65	93.44	96.47

CO_2 transport

There are no CO_2 transport networks across Europe yet and therefore this work proposes CO_2 pipeline networks which would connect each steel plant to an off-shore storage location. Two scenarios are considered, individual approach and collaborative approach. In the individual approach, the CO_2 transport considers a direct pipeline from each individual plant to the closest off-shore storage location. In the collaborative case, two or more plants share the pipeline to the storage site. To account for the various issues related to pipeline construction, the straight line distance, obtained within the ArcGIS software, is increased by extra 20% for on-shore pipelines and 10% for off-shore pipelines. All distances are expressed in kilometres. The connection between the plants in the collaborative network is identified using a minimum spanning tree algorithm in GAMS (GAMS, n.d.), referred to as the *CO_2 TranStorage* module of the model. Figure 6 in the manuscript demonstrates the considered CO_2 pipeline networks.

Transport cost curves provided by the IEAGHG (IEAGHG, 2005) are used to calculate the specific CO_2 transport cost for each plant. All 5 steps, listed in the report, are followed to determine:

Step 1: Pipeline diameters;

Step 2: Pipeline investment costs;

Step 3: Power use and costs for booster stations (electricity prices considered average 2017 values provided in Eurostat (Eurostat, 2017));

Step 4: Annual transport costs;

Step 5: The final specific transport costs.

In the case of collaborative networks, CO_2 transport for each plant is considered along the whole route until reaching the CO_2 storage, not only until the next plant. The share of the cost is defined according to plants' share of the total CO_2 volume flowing through the evaluated segment. Due to sharing the costs of the pipeline network used by two or more plants, the costs have usually decreased for all plants, even though CO_2 travels a longer distance in total. As this study uses estimates performed in 2005, the final values are scaled by an inflation factor of 1.20 (Official Data Foundation, 2018). In addition, it is important to note that the analysis of CO_2 transport cost assumes a concurrent development of the whole CO_2 pipeline network. i.e. all plants start to transport CO_2 on the same day. This means all pipelines are straight away designed based on plateau flow, which is in practice close to impossibility. In reality, pipeline network is built gradually, which would raise additional costs due to unused capacity – aspect not considered within this analysis.

CO_2 storage

Considering the current development, CO_2 storage is considered only off-shore in either saline aquifers or depleted oil and gas fields. CO_2 storage capacity and locations are taken from the Chalmers CO_2 storage database (Kjärstad and Johnsson, 2007). Cost of CO_2 storage is taken from the ZEP report (ZEP, 2011) and also scaled by an inflation factor of 1.09 for 2010 to 2017 (Official Data Foundation, 2018).

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