

SUPPLEMENTARY MATERIAL

Substitution of fossil coal with hydrochar from agricultural waste in the electric arc furnace steel industry: a comprehensive Life Cycle Analysis

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1. Mass and energy balance calculations

Mass balance on the HTC process has been carried out on gas, solid, and liquid phase. Table S1 lists the average data used for the HTC process scale-up based on literature values [1].

Table S1. Reference data for the scale-up process [1].

Parameter	Symbol	Unit	
Heating			
Reactor volume	V_{reactor}	m^3	1
Surface area	A_r	m^2	5.899
Thermal conductivity of insulation	λ	W/m K	0.042
Insulation thickness	s	m	0.075
Efficiency of the heating element	η_{heat}	%	74
Starting and outside temperature	$T_0 = T_{\text{out}}$	$^{\circ}\text{C}$	25
Stirring			
Impeller diameter	d	m	0.373
Type of impeller	N_p	/	0.79
Rotational speed	N	$1/\text{s}$	1.417
Efficiency of stirring	η_{stirr}	%	90
Filtration			
Filtration energy consumption	E_{filt}	kWh/t	10
Drying			
Specific heat capacity	$c_{p,\text{liq}}$	kJ/kg K	4.186
Drier efficiency	η_{heat}	%	80
Boiling temperature	T_{boil}	$^{\circ}\text{C}$	100
Starting temperature	T_0	$^{\circ}\text{C}$	25
Enthalpy of evaporation	ΔH_{vap}	kJ/kg	2571
Milling			
Milling energy consumption	E_{mill}	kWh/t	16
Pumping			
Gravitational acceleration	g	m/s^2	9.81
Height different	Δh	m	4.2
Milling efficiency	η_{mill}	%	75

1.2 Milling energy consumption

The raw feedstock is generally ground to an adequate particle size before being sent to the reactor. The energy consumption of a mill mainly depends on the size of the final particles,

the material to be ground and the type of grinding. A value of 16 kWh/ton of ground material was chosen as energy consumption for milling (E_{milling}), according to the literature [1]:

$$E_{\text{milling}} = 16 * m_{\text{biomass,HTC}} \text{ [kWh]}$$

where $m_{\text{biomass,HTC}}$ is the sum of the mass of VP and EGM. In detail, $m_{\text{biomass,HTC}}$ was determined as a function of the carbon content in 12 kg of coal, which is used per ton of steel produced in the EAF [2,3]. Thus, to substitute 12 kg of metallurgical coal [2,3] with a carbon content of 85%, 16.8 kg of hydrochar with a carbon content of 60.86% on a dry basis is needed. By considering the mass yield on a dry basis of the hydrochar equal to 52.64% [4], the total solid content of the biomass feedstock ($m_{\text{biomass,HTC,db}}$) results in 31.8 kg, which is a blend of 50% wt of VP and EGM. With a moisture content of 42% and 71% [4] respectively for VP and EGM, the total $m_{\text{biomass,HTC}}$ was 82.3 kg/ton of molten steel.

1.3 Thermal energy for HTC

The thermal energy required during the reaction stage was calculated as the energy to raise the reaction mixture to the set temperature and to keep it for the duration of the reaction (E_{react}).

$$E_{\text{react}} = \frac{E_{\text{heat}} + E_{\text{loss}}}{\eta_{\text{heat}}} \text{ [kWh]}$$

E_{heat} is the energy for raising the temperature:

$$E_{\text{heat}} = \left(c_{p \text{ biomass,HTC}} * m_{\text{biomass,HTC,db}} * (T_r - T_o) + m_{\text{vinasse}} * (H_{\text{vinasse},Tr} - H_{\text{vinasse},T_o}) \right) * 0.000278 \text{ [kWh]}$$

where:

- $c_{p \text{ biomass,HTC}}$ is the specific heat capacity of dry biomass (VP+EMG) [2.18 kJ/kg K] [4];
- $m_{\text{biomass,HTCdb}}$ is the mass of dry biomass in the inlet of the HTC reactor ($m_{\text{VP,db}} + m_{\text{EGM,db}}$) [kg];
- T_r is the reaction temperature (246.6 °C);
- T_o is the entering temperature of the feedstock reached after the regenerative heat exchanger (HE) ($T_o = 109.8$ °C);
- 0.000278 is the conversion factor kWh/kJ.
- m_{liq} is the mass of vinasse entering the reactor (400.1 kg);
- $H_{\text{liq},Tr}$ is the enthalpy of vinasse at 246.6°C (before phase transition to steam) ($H_{\text{liq},Tr} = 1009.3$ kJ/kg);

- $H_{liq,T0}$: is the enthalpy of vinasse at 109.8 °C (reached after the regenerative heat exchanger (HE), $H_{liq,T0} = 457.1$ kJ/kg);
- 0.000278 is the conversion factor kWh/kJ;

E_{loss} the energy related to the heat lost on the reactor surface and η_{heat} the efficiency of the heating device.

$$E_{loss} = A * \frac{\lambda}{s} * (T_r - T_{out}) * t / 1000 [kWh]$$

- A_r : surface area of the reactor [m²];
- λ : thermal conductivity of the insulation material [W/m K]
- s : the thickness of the insulation [m]
- T_r : the reaction temperature (246.6 °C);
- T_o : the temperature of the external environment (25 °C);
- t : the residence time (2.6 h);

and η_{heat} the efficiency of the heating device [1].

The thermal energy required for HTC heating is partly recovered by the heat exchanger and the remaining contribution is provided by an external heating source.

1.4 Electric energy HTC

Electrical energy is considered the energy required for stirring and pumping.

During the reaction stirring energy is consumed depending on the type (N_p) and diameter (d) of the impeller, the stirring rate (N), the density of the reaction mixture (ρ_{mix}) as well as the reaction time (t) and the impeller system efficiency (η_{stirr}). The following equation was used:

$$E_{stirr} = \frac{(N_p * \rho_{mix} * N^3 * d_{rotor}^5) * t}{\eta_{stirr} * 1000} [kWh]$$

In this work, an axial flow impeller (hydrofoil type) is assessed as stirrer type and turbulent flow is considered to be generated during stirring, leaving the power number constant for the calculations [5]. Moreover, the density of the reaction mixture was assumed equal to 1000 kg/m³.

Since the slurry (m_{slurry}) is transferred to the filtration stage through the pumping system, as well as the vinasse ($m_{vinasse}$) from the heat exchanger to the HTC reactor, the electrical energy was calculated by considering the efficiency of the pump η_{pump} , the mass to be transferred m

($m_{\text{slurry}} + m_{\text{vinasse}}$), the gravitational acceleration g , and a height different Δh [1], the energy consumption in turbulent flow as follows:

$$E_{\text{pump}} = \frac{m * g * \Delta h}{\eta_{\text{pump}}} * 0.000278 [kWh]$$

A safety factor of 10 % was considered.

1.5 Electric energy for slurry filtration (solid-liquid separation)

One of the main influencing factors on energy consumption during filtration is the particle size of the slurry. Since during the experimental laboratory procedure the particle size of the solid fraction was lower than 500 μm , for this study, the filtration process was supposed to be energy intensive. For this reason, the energy consumption during the filtration stage ($E_{\text{filtration}}$) was estimated 10 kWh/ton [1].

$$E_{\text{filtration}} = 10 * m_{\text{slurry}} [kWh]$$

The dry content of hydrochar after the filter press was assumed equal to 60 wt % [6].

1.6 Dryer

Drying was applied to remove the residual hydrochar moisture. After the filter press, wet hydrochar (relative humidity = 40 wt%) was assumed to be dried up to a solid content equal to 8 wt%, according to the literature [7,8]. Thus, the amount of water to be removed was obtained as the difference of the water between wet and dried hydrochar.

1.7 Thermal energy to evaporate water

The thermal energy required to remove water was calculated as follows:

$$E_{\text{dryer}} = \frac{c_{p,\text{liq}} * m_{\text{liq}} * (T_{\text{boil}} - T_0) + \Delta H_{\text{steam}} * m_{\text{steam}}}{3600 * \eta_{\text{dryer}}} [kWh]$$

Where:

- $c_{p,\text{liq}}$ is the specific heat capacity of water at 25 °C (4.186 kJ/kg K);
- m_{liq} is the amount of water to be evaporated [kg];
- T_{boil} is 100 °C;
- T_0 is the room temperature (25 °C);
- ΔH_{steam} is the latent heat of water 2571 kJ/kg;
- m_{steam} is the amount of steam to be produced equal to m_{liq} [kg];
- η_{dryer} is the efficiency factor of the dryer [1];

The total amount of steam ($m_{\text{steam}} = m_{\text{liq}} = 9.7 \text{ kg}$) was calculated assuming an 8 wt % of moisture after drying.

1.8 Heat exchanger

Energy from the slurry exiting the HTC is recovered to preheat the liquid feedstock (vinasse) entering into the HTC reactor, in a regenerative heat exchanger operating in continuous mode. A temperature of 35°C was established for the spent liquor leaving the heat exchanger in order to satisfy the mesophilic conditions for anaerobic digestion [9]. The temperature of the vinasse entering the HTC reactor ($T_{\text{vinasse,OUT}}$) was determined according to the following relation:

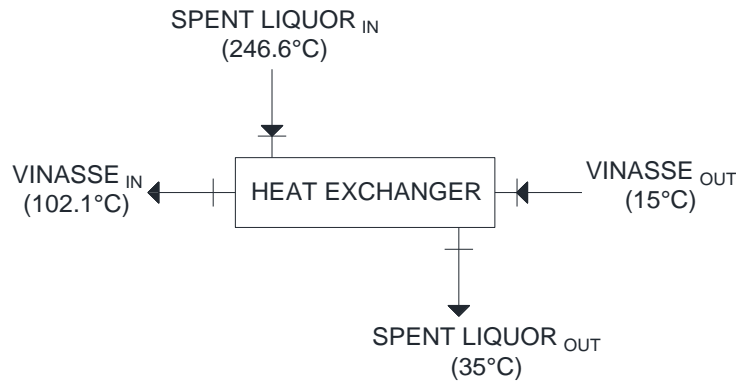


Figure S1. Scheme of heat exchanger in which vinasse is heated by hot spent liquor.

$$m_{\text{vinasse}} * c_{p,\text{vinasse}} * (T_{\text{vinasse,OUT}} - T_{\text{vinasse,IN}}) = m_{\text{SL}} * (H_{\text{SL,OUT}} - H_{\text{SL,IN}})$$

where:

- $c_{p,\text{vinasse}}$ is the specific heat capacity of vinasse assumed equal to 4.186 kJ/kg K);
- m_{vinasse} is the mass of vinasse in the inlet of the HTC reactor [kg];
- $T_{\text{vinasse,IN}}$ is the initial temperature of the vinasse (15 °C);
- m_{SL} is the mass of the hot spent liquor leaving the HTC reactor [kg];
- $H_{\text{SL,OUT}}$ is the enthalpy of the spent liquor at 35°C in non-saturated conditions (146.56 kJ/kg);
- $H_{\text{SL,IN}}$ is the enthalpy of the spent liquor at 246.6°C in non-saturated conditions (1009.28 kJ/kg);

The temperature of the slurry out of the heat exchanger was determined (102.1°C).

1.9 Gas balance calculations

Carbon (C) yields were applied to carry out the balance for gas. The hydrochar yield in terms of C was calculated as follows:

$$HY_C = \frac{\%C_{HC} * m_{HC,db}}{(\%C_{VP} * m_{VP,db}) + (\%C_{EGM} * m_{EGM,db}) + \left(\frac{TOC_{vinasse} * L_{vinasse}}{1000}\right)} * 100 \text{ [%]}$$

where $L_{vinasse} = m_{vinasse}/\rho_{vinasse}$ and $\rho_{vinasse}$ was considered equal to 1000 kg/m³.

HY_C resulted equal to 60.23 wt %.

The liquid (spent liquor) yield in terms of C was calculated as follows:

$$LY_C = \frac{TOC_{spent liquor} * m_{spent liquor}}{(\%C_{VP} * m_{VP,db}) + (\%C_{EGM} * m_{EGM,db}) + \left(\frac{TOC_{vinasse} * L_{vinasse}}{1000}\right)} * 100 \text{ [%]}$$

LY_C resulted equal to 11.08 wt %.

The gas yield in terms of C was calculated as follows:

$$GY_C (\%) = 100 - LY_C - HY_C$$

where all the terms were already defined previously.

Thus, $GY_C (\%)$ resulted equal to 28.69 wt %.

Then, the mass flow of carbon in the gas was calculated as:

$$m_{C \text{ gas}} = GY_C (\%) * \left((\%C_{VP} * m_{VP,db}) + (\%C_{EGM} * m_{EGM,db}) + \left(\frac{TOC_{vinasse} * L_{vinasse}}{1000}\right) \right)$$

where all the terms were already known.

Further, the carbon converted into the gas phase was assumed to be a mixture of CO₂ and CO according to the literature [10]

$$m_{gas} = \frac{x_{CO_2} * PM_{CO_2} + x_{CO} * PM_{CO}}{PM_C} * m_{C \text{ gas}} [kg]$$

where:

- X_{CO_2} is the percentage of CO₂ in gas (92 vol %) [10];
- X_{CO} is the percentage of CO in gas (8 vol %) [10];

- PM_{CO_2} is the molecular weight of CO_2 (44 g/mol);
- PM_{CO} is the molecular weight of CO (28 g/mol);
- PM_C is the molecular weight of C (12 g/mol);

This gas mixture has been directly emitted into the atmosphere, so the emissions of biogenic CO_2 can be calculated.

Gas density has been calculated using the ideal gas law (0 °C, and 1 atm):

$$\rho_{gas} = \frac{P}{RT} * (x_{CO_2} * PM_{CO_2} + x_{CO} * PM_{CO}) \text{ [kg/m}^3\text{]}$$

where:

- P is equal to 101 325 Pa;
- T is the temperature of 0 °C (273.15 K);
- R is the universal gas constant (8.314 J/mol K);

and all the other terms were already defined above.

The gas volume was calculated as:

$$V_{gas} = \frac{m_{gas}}{\rho_{gas}} \text{ [m}^3\text{]}$$

Lastly, CO_2 and CO emissions were calculated using these equations:

$$m_{CO_2} = x_{CO_2} * V_{gas} * \frac{P * PM_{CO_2}}{R * T} \text{ [kg } CO_2\text{]}$$

$$m_{CO} = x_{CO} * V_{gas} * \frac{P * PM_{CO}}{R * T} \text{ [kg } CO\text{]}$$

Resulting in 17.82 kg CO_2 and 0.99 kg CO .

2. LCA results

Table S2. Characterisation impact results of the production and usage of hydrochar.

Impact category	Unit	Ereact	Estirr	Efiltration	Edryer	Emill	Epump	Anaerobic Digestion	Transport
Global warming	kg CO2 eq	2.71E+01	1.92E-02	7.56E-01	2.49E+00	5.07E-01	3.45E-02	1.32E+00	5.13E+00
Stratospheric ozone depletion	kg CFC11 eq	6.12E-06	1.24E-08	4.90E-07	5.63E-07	3.29E-07	2.24E-08	7.95E-07	3.61E-06
Ionizing radiation	kBq Co-60 eq	2.61E-02	1.63E-04	6.44E-03	2.40E-03	4.31E-03	2.94E-04	7.91E-03	4.15E-02
Ozone formation. Human health	kg NOx eq	1.74E-02	3.31E-05	1.30E-03	1.60E-03	8.73E-04	5.95E-05	1.79E-03	7.72E-03
Fine particulate matter formation	kg PM2.5 eq	4.84E-03	2.18E-05	8.59E-04	4.45E-04	5.75E-04	3.92E-05	1.18E-03	4.35E-03
Ozone formation. Terrestrial ecosystems	kg NOx eq	1.81E-02	3.37E-05	1.33E-03	1.66E-03	8.89E-04	6.06E-05	1.82E-03	8.15E-03
Terrestrial acidification	kg SO2 eq	1.43E-02	6.41E-05	2.52E-03	1.31E-03	1.69E-03	1.15E-04	3.44E-03	9.65E-03
Freshwater eutrophication	kg P eq	6.17E-05	7.73E-07	3.05E-05	5.67E-06	2.04E-05	1.39E-06	3.42E-04	6.38E-04
Marine eutrophication	kg N eq	6.20E-06	5.12E-08	2.02E-06	5.70E-07	1.35E-06	9.22E-08	9.90E-04	1.06E-05
Terrestrial ecotoxicity	kg 1.4-DCB	1.92E+00	6.02E-02	2.37E+00	1.76E-01	1.59E+00	1.08E-01	3.14E+00	7.62E+01
Freshwater ecotoxicity	kg 1.4-DCB	1.20E-03	6.52E-06	2.57E-04	1.10E-04	1.72E-04	1.17E-05	2.05E-03	1.27E-02
Marine ecotoxicity	kg 1.4-DCB	5.43E-02	4.46E-05	1.76E-03	4.99E-03	1.18E-03	8.03E-05	4.74E-03	5.81E-02
Human carcinogenic toxicity	kg 1.4-DCB	4.33E-02	2.46E-04	9.69E-03	3.98E-03	6.50E-03	4.43E-04	2.53E-02	6.23E-02
Human non-carcinogenic toxicity	kg 1.4-DCB	2.14E-01	4.45E-03	1.75E-01	1.97E-02	1.17E-01	8.01E-03	6.25E-01	1.45E+00
Land use	m2a crop eq	8.53E-02	5.47E-04	2.16E-02	7.85E-03	1.44E-02	9.85E-04	2.89E-02	2.39E-01
Mineral resource scarcity	kg Cu eq	6.77E-03	3.84E-05	1.51E-03	6.23E-04	1.01E-03	6.91E-05	3.30E-03	1.26E-02
Fossil resource scarcity	kg oil eq	1.12E+01	5.83E-03	2.30E-01	1.03E+00	1.54E-01	1.05E-02	2.98E-01	1.74E+00
Water consumption	m3	9.05E-03	3.48E-04	1.37E-02	8.32E-04	9.19E-03	6.27E-04	-1.36E-01	9.75E-03

Table S3. Characterisation impact results of the production and usage of fossil coal.

Impact category	Unit	F-EAF	Anode	Argon	Electric arc furnace converter	Ferrosilicon	Hard coal	Iron scrap	Natural gas	Nitrogen	Oxygen	Quicklime	Refractory	Electricity	Electric arc furnace dust	Electric arc furnace secondary metallurgy slag	Electric arc furnace slag	Inert waste. for final disposal
Global warming	kg CO2 eq	4.41E+01	2.98E+00	1.51E+00	4.90E+00	3.29E+01	5.49E+00	3.85E+01	4.84E+00	8.02E-01	1.33E+01	6.86E+01	2.94E+01	2.22E+02	4.83E+00	5.01E+00	4.76E+01	5.68E-02
Stratospheric ozone depletion	kg CFC11 eq	0.00E+00	2.30E-06	7.31E-07	1.42E-06	1.08E-05	1.47E-06	1.90E-05	5.90E-06	3.88E-07	6.43E-06	7.25E-06	7.06E-06	1.45E-04	7.49E-07	7.76E-07	7.26E-06	3.62E-08
Ionizing radiation	kBq Co-60 eq	0.00E+00	5.97E-02	5.57E-02	2.01E-02	2.23E-01	1.43E-02	3.91E-01	3.05E-03	2.93E-02	4.89E-01	1.54E-01	6.93E-02	1.90E+00	1.47E-02	1.52E-02	1.42E-01	6.45E-04
Ozone formation. Human health	kg NOx eq	8.99E-02	7.34E-03	2.72E-03	1.60E-02	9.06E-02	2.45E-02	2.50E-01	9.34E-03	1.50E-03	2.42E-02	4.24E-02	6.27E-02	3.72E-01	1.20E-02	1.25E-02	1.17E-01	4.33E-04
Fine particulate matter formation	kg PM2.5 eq	3.26E-02	5.90E-03	2.23E-03	1.03E-02	1.83E-01	1.32E-02	1.01E-01	3.80E-03	1.18E-03	1.96E-02	2.13E-02	2.77E-02	2.33E-01	3.98E-03	4.12E-03	3.90E-02	1.22E-04
Ozone formation. Terrestrial ecosystems	kg NOx eq	9.76E-02	7.64E-03	2.74E-03	1.66E-02	9.51E-02	2.47E-02	2.55E-01	1.00E-02	1.52E-03	2.44E-02	4.36E-02	6.39E-02	3.78E-01	1.22E-02	1.26E-02	1.19E-01	4.42E-04
Terrestrial acidification	kg SO2 eq	6.02E-02	1.58E-02	5.60E-03	3.00E-02	1.17E-01	4.11E-02	2.50E-01	1.16E-02	2.98E-03	4.93E-02	5.45E-02	5.23E-02	6.94E-01	9.80E-03	1.02E-02	9.59E-02	2.71E-04
Freshwater eutrophication	kg P eq	0.00E+00	9.81E-04	1.70E-04	3.40E-04	1.88E-03	1.60E-03	4.46E-03	3.52E-05	9.07E-05	1.50E-03	2.03E-03	4.20E-03	8.41E-03	2.42E-04	2.33E-04	2.23E-03	1.02E-05
Marine eutrophication	kg N eq	0.00E+00	4.62E-06	6.42E-06	7.25E-05	1.18E-04	2.22E-05	2.90E-04	5.31E-06	3.37E-06	5.60E-05	1.65E-05	6.43E-05	3.84E-04	5.53E-06	5.73E-06	5.42E-05	3.39E-07
Terrestrial ecotoxicity	kg 1,4-DCB	4.61E+02	4.67E+00	1.73E+00	4.45E+01	5.06E+01	5.25E+00	1.09E+03	1.03E+00	1.09E+00	1.61E+01	1.12E+02	3.53E+01	2.33E+02	1.08E+01	1.11E+01	1.00E+02	4.67E-01
Freshwater ecotoxicity	kg 1,4-DCB	1.37E-02	3.43E-03	5.08E-04	1.52E-02	1.64E-02	2.45E-03	8.39E-02	1.13E-03	2.96E-04	4.60E-03	8.79E-03	1.48E+00	4.80E-02	3.64E-01	7.79E-02	2.08E+01	9.31E-05
Marine ecotoxicity	kg 1,4-DCB	3.10E-01	1.36E-02	2.14E-03	4.30E-02	5.03E-02	6.69E-03	6.25E-01	1.15E-02	1.26E-03	1.94E-02	9.67E-02	2.06E+00	2.52E-01	5.48E-01	1.22E-01	3.12E+01	4.03E-04
Human carcinogenic toxicity	kg 1,4-DCB	1.04E-01	5.82E-02	1.25E-02	5.47E-01	4.87E-01	3.91E-02	1.25E+00	2.86E-02	6.79E-03	1.11E-01	1.00E-01	2.28E+00	1.24E+00	2.83E+01	6.01E+00	1.77E+03	7.15E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	2.94E+01	3.32E-01	3.20E-01	3.03E+00	7.06E+00	2.98E-01	5.63E+01	1.10E-01	1.71E-01	2.82E+00	2.60E+00	7.25E+01	2.72E+01	5.06E+01	6.43E+00	7.24E+01	1.10E-02
Land use	m2a crop eq	0.00E+00	1.47E-01	4.09E-02	1.39E+00	7.21E-01	3.33E-01	4.55E+00	7.93E-02	2.23E-02	3.64E-01	3.48E-01	3.66E-01	5.07E+00	1.47E-01	1.52E-01	1.43E+00	-3.28E-03
Mineral resource scarcity	kg Cu eq	0.00E+00	4.25E-03	2.01E-03	1.16E-01	8.90E-02	6.43E-03	6.30E-01	5.30E-03	1.10E-03	1.78E-02	7.25E-03	7.64E-02	2.06E-01	1.83E-02	1.90E-02	1.81E-01	1.31E-04
Fossil resource scarcity	kg oil eq	0.00E+00	2.79E+00	4.09E-01	1.11E+00	9.08E+00	6.94E+00	1.14E+01	7.53E+00	2.15E-01	3.56E+00	6.45E+00	5.21E+00	6.76E+01	6.99E-01	7.24E-01	6.81E+00	3.00E-02
Water consumption	m3	4.25E+00	7.84E-03	8.35E-02	4.66E-02	1.93E-01	1.07E-02	2.30E-01	3.44E-03	4.41E-02	7.38E-01	3.30E-02	5.30E-02	3.96E+00	1.68E-02	1.75E-02	1.66E-01	1.12E-03

References

- [1] Piccinno F, Hischier R, Seeger S, Som C. From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies. *Journal of Cleaner Production* 2016;135:1085–97. <https://doi.org/10.1016/j.jclepro.2016.06.164>.
- [2] Norgate T, Langberg D. Environmental and Economic Aspects of Charcoal Use in Steelmaking. *ISIJ International* 2009;49:587–95. <https://doi.org/10.2355/isijinternational.49.587>.
- [3] Echterhof T. Review on the Use of Alternative Carbon Sources in EAF Steelmaking. *Metals* 2021;11:222. <https://doi.org/10.3390/met11020222>.
- [4] Barbanera M, Cardarelli A, Carota E, Castellini M, Giannoni T, Ubertini S. Valorization of winery and distillery by-products by hydrothermal carbonization. *Sci Rep* 2021;11:23973. <https://doi.org/10.1038/s41598-021-03501-7>.
- [5] Albright L, editor. *Albright's Chemical Engineering Handbook*. 0 ed. CRC Press; 2008. <https://doi.org/10.1201/9781420014389>.
- [6] Lucian M, Volpe M, Merzari F, Wüst D, Kruse A, Andreottola G, et al. Hydrothermal carbonization coupled with anaerobic digestion for the valorization of the organic fraction of municipal solid waste. *Bioresource Technology* 2020;314:123734. <https://doi.org/10.1016/j.biortech.2020.123734>.
- [7] Mendecka B, Lombardi L, Micali F, De Risi A. Energy Recovery from Olive Pomace by Hydrothermal Carbonization on Hypothetical Industrial Scale: a LCA Perspective. *Waste Biomass Valor* 2020;11:5503–19. <https://doi.org/10.1007/s12649-020-01212-0>.
- [8] Mannarino G, Caffaz S, Gori R, Lombardi L. Environmental Life Cycle Assessment of Hydrothermal Carbonization of Sewage Sludge and Its Products Valorization Pathways. *Waste Biomass Valor* 2022;13:3845–64. <https://doi.org/10.1007/s12649-022-01821-x>.
- [9] Mannarino G, Sarrion A, Diaz E, Gori R, De La Rubia MA, Mohedano AF. Improved energy recovery from food waste through hydrothermal carbonization and anaerobic digestion. *Waste Management* 2022;142:9–18. <https://doi.org/10.1016/j.wasman.2022.02.003>.
- [10] Basso D. Hydrothermal carbonization of waste biomass Daniele Basso 2016:1–277.