DOI 10.36146/2026_0708_44

Ecological assessment of the use of hydrochar in EAF operation based on an LCA approach

C. Gondorf, F. Kaiser, T. Echterhof

The environmental impacts associated with using hydrochar in electric arc furnace (EAF) steelmaking were evaluated using a life cycle assessment (LCA). The goal is to quantify potential environmental impacts and identify key drivers and trade-offs when hydrochar substitutes conventional fossil carbon in EAF practice. The LCA follows ISO 14040/14044 principles, applying a functional unit of "1 tonne of liquid steel produced in an EAF" and comparing a baseline fossil-carbon scenario with multiple hydrochar integration scenarios. Impact categories include climate change, particulate matter formation, terrestrial acidification, water eutrophication, resource use, and water-related indicators. Results indicate that hydrochar can meaningfully reduce fossil carbon demand and associated greenhouse gas emissions, particularly when produced from residue streams with low upstream burdens and when HTC/drying energy is supplied by low-carbon sources or recovered heat. However, benefits may be offset by higher processing energy, increased ash handling, and potential trade-offs in terrestrial acidification/water eutrophication depending on feedstock cultivation and nutrient emissions. Hotspots typically include energy for dewatering/drying and the electricity mix, making decarbonized energy supply and process integration critical. The study provides guidance on environmentally robust hydrochar supply chains and operational conditions under which hydrochar contributes to lower-impact EAF steelmaking.

KEYWORDS: HYDROCHAR; EAF STEELMAKING; LIFE CYCLE ASSESSMENT; CARBON CARRIERS SUBSTITUTION; SUSTAINABILITY; ORGANIC RESIDUALS.

INTRODUCTION

Electric Arc Furnaces (EAFs) rely on carbonaceous materials (e.g., anthracite, coke breeze, or synthetic graphite) for slag foaming, oxygen refining, and energy efficiency. Replacing fossil-derived carbon with hydrochar, produced via hydrothermal carbonization (HTC) of biomasses or residues, could lower the environmental footprint of steelmaking. Yet the net benefit depends strongly on feedstock origin, process energy, and operational substitution rates. This study presents an ecological assessment of hydrochar use in EAF operation based on a life cycle assessment (LCA) framework. LCA is a standardized method for quantifying and assessing the environmental burdens of product systems across defined system boundaries. It is widely applied by industry, policy makers, and environmental organizations to support environmental strategy development and informed material

Carsten Gondorf, Felix Kaiser, Thomas Echterhof
RWTH Aachen University, Germany

selection; accordingly, it provides a suitable framework for assessing hydrochar substitution in EAF operation (1).

Following ISO EN 14040 and ISO EN 14044, a systematic data collection and transparent reporting of results were implemented. This structured approach enables the identification of potential hotspots and previously overlooked weaknesses along the process chain, thereby highlighting optimization opportunities (2, 3). First, the goal and scope of the LCA were defined. Subsequently, a life cycle inventory (LCI) was compiled by identifying and quantifying the key material and energy flows within the system. A material flow model was developed, including data collection, allocation choices, calculation of FU-related material flows, and the derivation of emissions and other relevant operating parameters. Based on the inventory, the life cycle impact assessment (LCIA) quantified the environmental impacts. In the interpretation phase, system boundaries and material flows were critically checked and validated, and results were evaluated for consistency and robustness. All assumptions, methodological steps, and result visualizations were documented.

The assessment distinguishes between integrated and non-integrated hydrochar production and investigates two EAF substitution pathways: replacing fossil carbon with fine-grained hydrochar for injection, and replacing fossil charged carbon with hydrochar agglomerates. For each pathway, the substitution rate of 100% biogenic carbon in therms of hydrochar instead of fossile carbon was investigated.

The Hydrochar, a carbon-rich solid fuel, was produced via hydrothermal carbonisation (HTC). The process is performed under oxygen-free conditions in subcritical liquid water, increasing the carbon content of the solid product through reactions such as hydrolysis, dehydration, decarboxylation, aromatisation, and recondensation (4). A key advantage of HTC is that it can process high-moisture feedstocks while still achieving high yields and a relatively high heating value of the resulting hydrochar (5, 6). The core unit is a heated, pressurised stirred reactor, operated under inert conditions via nitrogen purging and monitored by temperature and pressure control. Table 1 shows the evaluation of utilising hydrochar produced from organic residues.

Tab.1 - Evaluation of utilising hydrochar produced from organic residues (7).

Sample	C	H	N	S	Moisture	Volatile	Ash	Fixed C	O
Lingyuan anthracite	77.38	3.61	0.86	0.90	0.84	13.21	15.02	70.93	1.35
Shenhua bituminous coal	65.12	4.05	0.92	0.34	5.05	35.88	8.58	49.49	15.94
Hydrochar from green waste	50.94	4.95	1.43	0.38	2.58	57.82	15.97	23.63	23.75
Hydrochar from organic fraction	58.61	6.72	2.24	0.31	2.11	68.76	12.88	16.25	17.13
Hydrochar from orange peel	58.06	5.08	1.56	0.16	3.51	59.66	6.18	30.65	25.45

LCA Goal and scope definition

The study compares fossil-based and biogenic carbon carriers by assessing the substitution of conventional carbon inputs with hydrochar in EAF steelmaking. Environmental impacts were quantified using the ReCiPe Midpoint method. The evaluated impact indicators comprise Global Warming Potential (GWP, climate change), Fossil Depletion Potential (FDP), Freshwater Eutrophication Potential (FEP), Human Toxicity Potential (HTP), Metal Depletion Potential (MDP), Natural Land Transformation Potential (NLTP), Ozone Depletion Potential (ODP), Photochemical Oxidant Formation Potential (POFP), Terrestrial Acidification Potential (TAP), and Water Use (WU). The modelling focuses on the EAF melting stage, while additionally accounting for relevant upstream and downstream processes to ensure a consistent comparison across cases. The functional unit (FU) is defined as 1 tonne of liquid tapped steel, and the system boundary is set according to a gate-to-gate approach (8, 3).

For this study, plant-specific operating data were collected, aligned, and analyzed. In collaboration with two steel plant, two site-specific baseline LCA models were established. The work started with a goal and scope definition tailored to the intended application and iteratively refined during model development. The overall aim is to compare the environmental performance of alternative process routes at the partner sites. For each scenario, the necessary process parameters were compiled. Remaining data gaps were addressed through transparent and well-justified assumptions.

Inventory analysis and calculation of environmental impacts

The life cycle inventory (LCI) comprises the collection and calculation of primary data in close collaboration with industrial partners, which were subsequently implemented in the LCA process models. To ensure consistent and comprehensive data acquisition, a standardized checklist for electric steelmaking process data was developed, derived from a generic EAF mass balance. Based on this framework, all relevant material and energy inputs as well as outputs associated with the EAF melting stage were identified and considered (figure 1 (l)). Modelling and impact calculations were performed in Umberto® LCA+ using datasets from ecoinvent®; figure 1 (r) illustrates the corresponding model structure for the base case for an EAF operation.

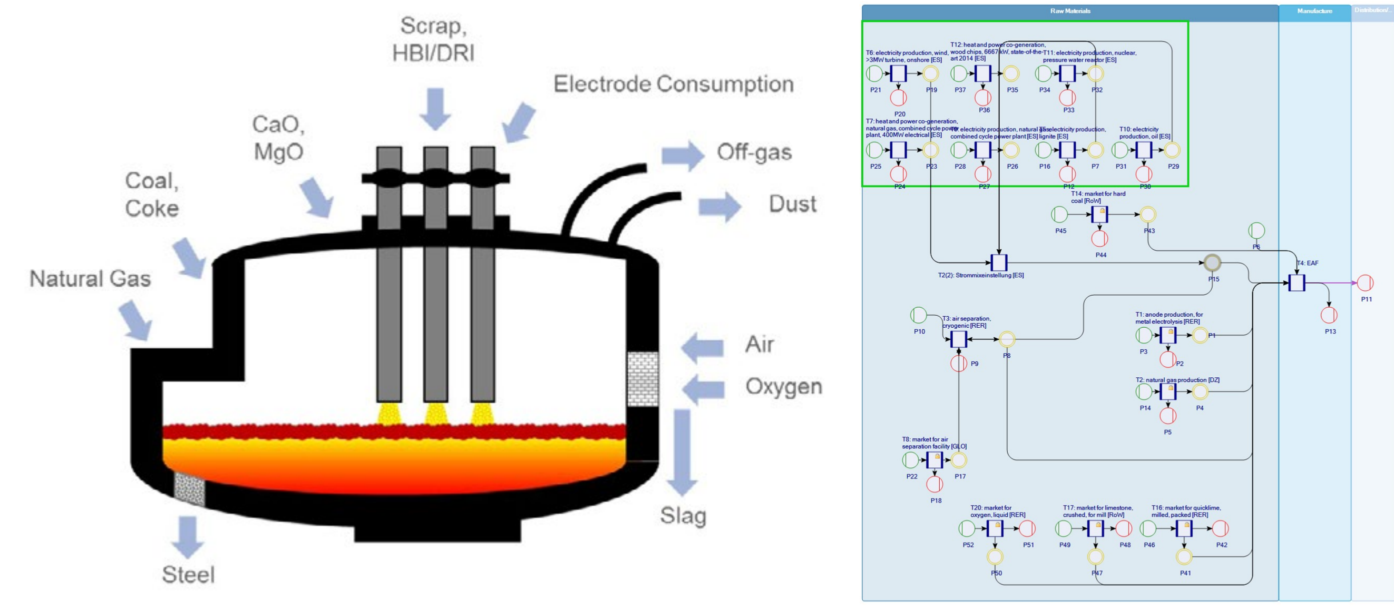

Fig.1 - General mass balance (l) and General LCA process model in Umberto® LCA+®.

To comply with confidentiality requirements, the LCI is interpreted in relative terms rather than reporting site-specific values. Across both plants, the substitution concept is implemented without changing the overall production function (1 t liquid tapped steel as functional unit) and with essentially constant major operating parameters such as electricity demand (approximately 410 – 420 kWh per tonne of steel), electrode consumption, flux addition and scrap charge. This indicates that the compared cases are designed to isolate the effect of the carbon carrier change while keeping the core EAF operation comparable.

The principal change between scenarios is the substitution of fossil carbon by hydrochar, differentiated by application route, one case targets injected carbon and the other targets charged carbon. Due to the assumed fixed-carbon content of hydrochar, the required hydrochar mass per functional unit is higher than the corresponding fossil-carbon mass to provide an equivalent fixed-carbon function. In the inventories, this manifests as an increase from about 7.0 – 7.3 kg/t fossil carbon to about 10.6 – 10.9 kg/t hydrochar. Aside from this substitution, no systematic shifts in auxiliary inputs are visible, suggesting that the modelling isolates carbon-carrier effects rather than attributing major operational changes to hydrochar use at the foreground level.

On the output side, liquid steel production is fixed at 1 t (FU), while by-products and process-related flows remain consistent across scenarios, including dust generation and slag. This inventory structure implies that differences observed in the subsequent impact assessment are expected to be driven primarily by upstream burdens of hydrochar production and logistics, the electricity and heat supply assumed for HTC and post-treatment, and the substitution of fossil-derived carbon by biogenic fixed carbon, rather than by changes in the EAF mass balance or main operating consumptions.

Table 2 summarizes the LCI for the hydrochar production via HTC per tonne of biowaste input. For the subsequent LCIA, mean inventory values were derived and applied as representative inputs to the model. In addition, a feedstock sensitivity analysis was performed to assess the influence of biomass variability on the results and to identify potential hotspots as well as optimization opportunities associated with different biowaste types.

Tab.2 - LCI per ton of biowaste (Units refer to: dw - dry weight basis) (9).

Category	Inputs & Outputs	Units	Green Waste	Food Waste	Organic fraction of MSC	Digestate
Input	Waste	ton (dw)	1	1	1	1
	Moisture content	%	45	84	34	59
	Electricity for pumping	kWh	0.003	0.003	0.003	0.003
	Thermal Energy	kWh	611.1	611.1	611.1	611.1
	Electricity for drying & pelletizing	kWh	40	40	40	40
	Electricity for reverse osmosis	kWh	0.54	0.37	0.62	0.56
Output	Raw hydrochar	ton (dw)	0.59	0.37	0.72	0.56
	Cleaned hydrochar pellets	ton (dw)	0.54	0.37	0.62	0.56
	Process waster	ton	0.5597	0.8543	0.4714	0.6678
	Ash	ton	0.0703	0.0179	0.1011	0.0597
	N in waste stream	ton	0.0011	0.0017	0.0008	0.0013
	P in waste stream	ton	0.0001	0.0001	0	0.0001
	K in waste stream	ton	0.0002	0.0008	0.0005	0.0009
	Carbon dioxide (CO_2)	ton	0.0624	0.0434	0.0257	0.0118
	Carbon monoxide (CO)	ton	0	0.0006	0.0004	0.0006
	Hydrogen (H_2)	ton	0	0.0001	0.0009	0

Regarding the process data of steel plant A, three scenarios with two different cases (production with energy mix and production with green energy mix) were investigated:

- Scenario 1: 100 % fossil carbon injection
- Scenario 2: 100 % hydrochar for injection (external production)
- Scenario 3: 100 % hydrochar for injection (internal production)

Table 3 presents a contribution analysis (normalized to 100% per impact category) for the EAF in case A. With the current mix, environmental burdens are largely driven by electric power and EAF off-gas. Electric power contributes strongly to climate change (42% GWP) and dominates fossil depletion (56% FDP) and freshwater eutrophication (77.1% FEP), while also being relevant for ozone depletion, photochemical oxidant formation, terrestrial acidification, and water use. EAF off-gas is the main hotspot for human toxicity (86.1% HTP), metal depletion (70.8% MDP), and natural land transformation (89.4% NLT), and remains a major contributor to photochemical oxidant formation and terrestrial acidification.

Under renewable electricity, the contribution of electric power decreases significantly for GWP and most air-related categories, and off-gas becomes negligible across indicators. As a result, consumables and utilities gain relative importance: oxygen dominates water use (65.3%), while natural gas and fossil carbon become more relevant for fossil depletion. Electric power still contributes substantially to metal depletion (49.1%), indicating that this category is influenced by upstream material requirements of the electricity system.

Tab.3 - LCIA of steel plant A (Production with energy mix, Scenario 1).

	Result of the impact assessment									
Medium	**GWP 100 [%]**	**FDP [%]**	**FEP [%]**	**HTP inf [%]**	**MDP [%]**	**NLTP [%]**	**ODP inf [%]**	**POFP [%]**	**TAP 100 [%]**	**WU [%]**
Production with energy mix, Scenario 1										
Electric power	42.0	56.0	77.1	13.1	28.0	7.3	56.6	29.2	42.1	32.1
Electrode consumption	0.4	1.3	0.1	0.2	0.1	0.2	2.1	0.4	0.6	0.2
Oxygen	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	50.0
Natural gas	0.2	5.9	0.1	0.0	0.1	0.0	0.1	0.2	0.1	0.1
Fossil carbon	0.8	4.5	6.1	0.1	0.3	2.5	0.4	1.8	2.5	0.3
Polymer	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.3	0.3	0.2
Lime	10.9	3.5	0.3	0.3	0.5	0.3	6.1	3.5	2.8	1.9
EAF offgas	45.5	28.6	16.0	86.1	70.8	89.4	34.6	64.6	51.6	15.2
Production with renewable energy, Scenario 1										
Electric power	7.1	8.5	24.1	20.9	49.1	7.6	6.9	9.6	17.5	11.4
Electrode consumption	0.6	2.7	0.4	0.1	0.1	0.2	4.5	0.6	0.9	0.3
Oxygen	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	65.3
Natural gas	0.3	12.3	0.2	0.0	0.1	0.0	0.1	0.3	0.2	0.1
Fossil carbon	1.3	9.3	20.2	0.1	0.2	2.5	0.9	2.3	3.5	0.4
Polymer	0.4	0.5	1.0	0.1	0.1	0.1	0.2	0.3	0.4	0.2
Lime	17.5	7.3	0.8	0.3	0.3	0.3	13.0	4.5	4.0	2.4
EAF offgas	72.8	59.4	53.1	78.4	50.0	89.1	74.3	82.4	73.5	19.8

For the most relevant scenarios for the hydrochar production, the impact category of Global Warming Potential, Freshwater Eutrophication Potential and Terrestrial Acidification Potential were used for further comparison. Table 4 shows contribution shares for GWP, FEP, and TAP, reported as external and internal results for plant A in Scenarios 2 and 3. With the current electricity mix, electricity supply dominates FEP (about 78%) and contributes around 42-43% to GWP and TAP, while EAF off-gas is the main hotspot for GWP (about 46%) and TAP (about 53%).

Lime remains a relevant contributor to GWP (about 11%). Charged hydrochar has only minor effects on GWP and TAP but contributes around 5% to FEP.

With renewable electricity, the contribution of electric power drops strongly (GWP ~7%, FEP ~25%, TAP ~18%), and the profile shifts to EAF off-gas as the dominant contributor across all three indicators (roughly 55-76%). Lime becomes more important for GWP (~18%). Charged hydrochar becomes more visible in FEP (about 14-18%) while remaining small for GWP and TAP. Differences between external and internal splits are generally small, indicating a stable hotspot ranking across accounting perspectives.

Tab.4 - LCIA of steel plant A (Production with energy mix, Scenario 2 & 3).

Medium	GWP 100 [%]	GWP 100 [%]	FEP [%]	FEP [%]	TAP 100 [%]	TAP 100 [%]
	External	Internal	External	Internal	External	Internal
Production with energy mix, Scenario 2 & 3						
Electric power	42.1	42.2	77.7	78.0	43.0	43.0
Electrode consumption	0.4	0.4	0.1	0.1	0.6	0.6
Oxygen	0.0	0.0	0.0	0.0	0.0	0.0
Natural gas	0.2	0.2	0.1	0.1	0.1	0.1
Charged hydrochar	0.3	0.3	5.4	5.0	0.4	0.2
Polymer	0.3	0.3	0.3	0.3	0.3	0.3
Lime	11.0	11.0	0.3	0.3	2.9	2.9
EAF offgas	45.7	45.7	16.1	16.2	52.7	52.8
Production with renewable energy, Scenario 2 & 3						
Electric power	7.2	7.2	24.7	26.0	18.1	18.2
Electrode consumption	0.6	0.6	0.4	0.5	0.9	0.9
Oxygen	0.0	0.0	0.1	0.1	0.0	0.0
Natural gas	0.3	0.3	0.2	0.2	0.2	0.2
Charged hydrochar	0.5	0.2	18.1	13.7	0.6	0.0
Polymer	0.4	0.4	1.1	1.1	0.4	0.4
Lime	17.6	17.7	0.9	0.9	4.1	4.1
EAF offgas	73.4	73.6	54.5	57.4	75.7	76.2

Regarding the process data of steel plant B, three scenarios with two different cases (production with energy mix and production with green energy mix) were investigated:

- Scenario 1: 100 % fossil charged carbon
- Scenario 2: 100 % hydrochar carbon pellets (external production)
- Scenario 3: 100 % hydrochar carbon pellets (internal production)

Table 5 provides the contribution analysis for the EAF case B (Scenario 1). Under the current mix, impacts are, again, mainly driven by electric power and EAF off-gas. Electric power contributes substantially to climate change (44.0% GWP) and dominates fossil depletion (56.6% FDP) and freshwater eutrophication (78.5% FEP); it is also relevant for ozone depletion (45.2%), photochemical oxidant formation (29.6%), terrestrial acidification (41.0%), and water use (40.8%). EAF off-gas is the key hotspot for human toxicity (91.9% HTP), metal depletion (87.6% MDP), and natural land transformation (93.3% NLT), and contributes strongly to photochemical oxidant formation (65.9%) and terrestrial acidification (54.1%). Oxygen supply is negligible for most categories but accounts for a large share of water use (42.7%). Lime shows a consistent secondary contribution, particularly to GWP (9.7%).

With renewable electricity, the contribution of electric power decreases strongly for climate change (6.5% GWP) and several air-related categories, but remains important for metal depletion (41.6%) and still contributes to freshwater eutrophication (19.4%). In this case, EAF off-gas becomes the dominant contributor for most categories, including GWP (73.6%), FDP (68.3%), FEP (58.1%), HTP (83.0%), NLT (91.2%), and ozone depletion (78.0%). At the same time, terrestrial acidification shifts markedly: lime becomes the main driver (78.2% TAP), while the off-gas contribution drops to zero, indicating that the remaining acidification burden is largely associated with upstream lime production rather than EAF emissions. Oxygen becomes the primary driver of water use (67.9%). Overall, the results show that decarbonizing electricity changes the hotspot structure, reducing the role of power for climate change but increasing the relative importance of off-gas and selected material inputs, underscoring the need for multi-indicator mitigation strategies.

Tab.5 - LCIA of steelplant B (Production with energy mix, Scenario 1).

Result of the impact assessment										
Medium	**GWP 100 [%]**	**FDP [%]**	**FEP [%]**	**HTP inf [%]**	**MDP [%]**	**NLTP [%]**	**ODP inf [%]**	**POFP [%]**	**TAP 100 [%]**	**WU [%]**
Production with energy mix, Scenario 1										
Electric power	44.0	56.6	78.5	7.5	11.5	4.1	45.2	29.6	41.0	40.8
Electrode consumption	0.4	1.3	0.1	0.1	0.1	0.2	2.4	0.4	0.6	0.2
Oxygen	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	42.7
Natural gas	0.1	1.9	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Fossil carbon	0.8	4.3	5.1	0.1	0.3	2.2	0.5	1.5	2.2	0.3
Lime	9.7	2.9	0.2	0.3	0.4	0.2	5.7	2.5	2.0	1.3
EAF offgas	45.0	33.1	16.0	91.9	87.6	93.3	46.2	65.9	54.1	14.7
Production with renewable energy, Scenario 1										
Electric power	6.5	7.2	19.4	16.4	41.6	5.7	5.3	10.4	18.4	9.5
Electrode consumption	0.7	3.1	0.5	0.1	0.1	0.2	4.7	0.0	0.0	0.0
Oxygen	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	67.9
Natural gas	0.1	4.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fossil carbon	1.5	10.2	21.2	0.1	0.2	2.5	0.9	3.8	3.4	2.0
Lime	17.5	6.8	0.7	0.3	0.3	0.2	11.0	85.9	78.2	20.6
EAF offgas	73.6	68.3	58.1	83.0	57.7	91.2	78.0	0.0	0.0	0.0

Again, the impact categories of Global Warming Potential, Freshwater Eutrophication Potential and Terrestrial Acidification Potential were used for further evaluation. Table 6 reports the contribution shares for plant B in Scenarios 2 and 3for the external and internal production of hydrochar. With the current electricity mix, electricity supply dominates FEP (about 79%) and contributes around 42-44% to GWP and TAP. EAF off-gas is the main contributor to GWP (about 45%) and accounts for the remaining share in FEP and TAP (about 16% and 55%, respectively). Lime shows a noticeable contribution to GWP (~10%) and TAP (~2%). Charged hydrochar remains small for GWP and TAP but contributes around 4-5% to FEP.

Under renewable electricity, the contribution of electric power decreases markedly (GWP ~6-7%, FEP ~20-21%, TAP ~19%). The remaining impacts are largely driven by EAF off-gas for GWP (~74-75%) and FEP (~60-63%). In contrast to case A, TAP shifts strongly to lime as the dominant hotspot (around 80-81%), while off gas becomes negligible for TAP. Charged hydrochar becomes more relevant for FEP (about 14-19%) but remains minor for GWP and TAP.

A feedstock sensitivity analysis was carried out by varying the HTC input between four representative biowaste types (green waste, food waste, organic fraction of MSW, and digestate) while keeping the EAF substitution rate conditions constant. The feedstocks differ primarily in moisture content (34-84% across the investigated wastes) and in the associated upstream burdens of the process-water stream (CO_2/phosphate-related contributions), which in turn changes the impact results. The total climate-change impact of hydrochar production ranges from 73.6 to 110.4 kg CO_2-eq per t biowaste (−18% to +23% relative to the feedstock mean), with the highest value obtained for green waste, mainly driven by the CO_2/phosphate-related contribution (62.4 kg CO_2-eq), whereas MSW shows the lowest total (25.7 kg CO_2-eq from CO_2/phosphates). Freshwater eutrophication exhibits the strongest relative sensitivity, varying from 0.020 to 0.100 kg P-eq (−72% to +40%); this spread is largely controlled by the CO_2/phosphate term (0.0018–0.083 kg P-eq), confirming that nutrient-related burdens of the liquid fraction dominate this indicator. Terrestrial acidification varies between 0.35 and 0.511 kg SO_2-eq (−11% to +30%), with digestate showing the highest value, consistent with its comparatively higher electricity and thermal-energy contributions.

Tab.6 - LCIA of steelplant B (Production with energy mix, Scenario 2 & 3).

Medium	GWP 100 [%]	GWP 100 [%]	FEP [%]	FEP [%]	TAP 100 [%]	TAP 100 [%]
	External	Internal	External	Internal	External	Internal
Production with energy mix, Scenario 2 & 3						
Electric power	44.2	44.2	79.1	79.3	41.8	41.9
Electrode consumption	0.4	0.4	0.1	0.1	0.6	0.6
Oxygen	0.0	0.0	0.0	0.0	0.0	0.0
Natural gas	0.1	0.1	0.0	0.0	0.0	0.0
Charged hydrochar	0.3	0.3	4.5	4.2	0.3	0.2
Lime	9.8	9.8	0.2	0.2	2.1	2.1
EAF offgas	45.2	45.2	16.1	16.2	55.2	55.3
Production with renewable energy, Scenario 2 & 3						
Electric power	6.6	6.6	19.9	21.1	18.9	19.0
Electrode consumption	0.7	0.7	0.5	0.5	0.0	0.0
Oxygen	0.0	0.0	0.1	0.1	0.0	0.0
Natural gas	0.1	0.1	0.1	0.1	0.0	0.0
Charged hydrochar	0.6	0.3	19.0	14.4	0.6	0.0
Lime	17.7	17.7	0.8	0.8	80.5	81.0
EAF offgas	74.3	74.5	59.7	63.0	0.0	0.0

Interpretation and reporting on the LCA results

Electricity is a key driver of climate change and the main contributor to fossil depletion and freshwater eutrophication, while EAF off-gas dominates toxicity- and land-related indicators and contributes strongly to photochemical oxidant formation and terrestrial acidification.

Secondary contributors include lime (relevant to climate change and, in some cases, acidification) and oxygen supply, which has limited influence on most categories but is a major driver of water use. Switching to renewable electricity shifts the contribution profile. The share of electric power decreases sharply for climate change and several air-related categories; however, metal depletion remains partly driven by electricity, indicating upstream material requirements in the electricity system. Under renewable electricity, remaining burdens are increasingly governed by direct process emissions and consumables. The life cycle impact assessment confirms that substituting fossil carbon carriers with biogenic alternatives in EAF steelmaking is technically feasible and can reduce the footprint of different impact categories. However, for Scenarios 2 and 3, hydrochar substitution does not substantially change the overall hotspot ranking at plant level, because electricity and off gas remain dominant. Charged hydrochar contributes only marginally to climate change and terrestrial acidification, but it is more relevant for freshwater eutrophication, especially under renewable electricity, where upstream burdens become more visible. Differences between internal and external results are generally small, and hotspot rankings remain stable, supporting the robustness of the qualitative interpretation. Uncertainty is mainly associated with limited primary off-gas data and background dataset choices for electricity and key inputs. Given the strong influence of off-gas and electricity, improved off-gas measurements and refined energy balances would significantly strengthen result validity. Overall, the results indicate that robust environmental improvements from hydrochar require not only fossil carbon substitution, but also low-impact hydrochar supply chains and broader measures targeting electricity, off-gas management, and major consumables (notably oxygen and lime).

CONCLUSION

This study applied an ISO 14040/14044-compliant LCA to evaluate hydrochar as a substitute for fossil carbon carriers in EAF steelmaking. Across plants and scenarios, the contribution analyses show that electricity supply and EAF off-gas dominate most impact categories under the current electricity mix. Electricity strongly drives climate change, fossil depletion, and freshwater eutrophication, while off-gas is the main hotspot for toxicity- and land-related categories and contributes substantially to photochemical oxidant formation and terrestrial acidification. Oxygen and lime are relevant for specific indicators, especially water use and acidification. Hydrochar can contribute to reducing the environmental footprint of EAF steelmaking, but benefits depend strongly on low-carbon energy for hydrochar production and EAF electricity, as well as improved characterization of off-gas emissions. Further primary measurements and refined modelling of hydrochar supply chains (integrated vs. non-integrated) are recommended to reduce uncertainty and support robust cross-category improvements.

Overall, process simulation via LCA provides a useful complement to industrial trials, enabling the analysis of non-measurable variables and supporting targeted optimization of EAF operation. Extending this modelling approach to other hydrochars could improve the efficiency and focus of future industrial-scale testing. Previous campaigns (e.g., GreenEAF2) further indicate elevated CO and CO_2 peaks as well as potentially higher N_2, H_2, H_2O, and CH_4 in the off-gas when biogenic carbon is applied, which should be considered in a holistic environmental and operational comparison. Higher reactivity and volatile content of the biogenic carbon can increase average CO and CO_2 concentrations in the off-gas, highlighting the importance of off-gas related effects when assessing overall performance in the upcoming industrial trials

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support from EU RFCS BioReSteel project (grant no. 101112383).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Carsten Gondorf: conceptualization (lead); data curation (lead); investigation (lead); methodology (equal); writing - original draft (lead).

Felix Kaiser: conceptualization (equal); data curation (supporting); writing - review and editing (supporting).
Thomas Echterhof: funding acquisition (lead); project administration (lead); writing—review and editing (supporting).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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