

Article

Resource Recovery from Stainless Steel Pickling Sludge: A Multi-Impact Life Cycle Assessment

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Abstract

The stainless steelmaking process generates substantial volumes of metal hydroxide sludge during neutralization after pickling. The sludge contains valuable materials, including fluorspar (CaF_2) and alloy-containing compounds. So far, life cycle assessment (LCA) of resource recovery and reuse pathways for pickling sludge remains absent in the literature. This study conducted a comprehensive LCA of a real-world Swedish case study in which the sludge is thermally processed into a usable product (Hydrofluss) and utilized in the argon oxygen decarburization (AOD) process in stainless steelmaking. Using the Product Environmental Footprint (PEF) 3.1 method and ecoinvent v3.11 in SimaPro v10.3.01, the results showed that using 1 ton of Hydrofluss can reduce the total life-cycle climate change impact by 91.6 kg CO_2eq , corresponding to a 6% reduction compared with a reference scenario relying on natural fluorspar and primary ferroalloys. The sensitivity analysis indicated that replacing fossil heating oils with renewable HVO100 in the Hydrofluss recovery process could substantially enhance the climate benefit of the studied system, resulting in a six-fold (540.3 kg) CO_2eq emission reduction. Beyond climate change, this study highlights the need for multi-impact LCAs to provide a more holistic understanding of the environmental implications of resource recovery and utilization systems. In a broader context, the findings can contribute to the development of more sustainable and circular resource flows and associated business models for stainless steelmaking.

Keywords: stainless steelmaking; pickling sludge; resource recovery; Hydrofluss; critical raw materials; metallurgy; LCA



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1. Introduction

Stainless steel comprises a broad group of corrosion-resistant, iron-based alloys primarily composed of iron (Fe), with a minimum chromium (Cr) content of 10.5%, and typically containing additional alloying elements such as nickel (Ni), manganese (Mn), and molybdenum (Mo), depending on the grade [1]. In 2024, global stainless steel production reached 62.62 million tons, while production in Europe amounted to 6.09 million tons, corresponding to increases of 7% and 1.5%, respectively, compared with 2023 [2]. However, Sverdrup & Olafsdottir [3] projected that stainless steels containing Mn-Cr-Ni would continue to increase in production until reaching a global peak around 2040, followed by a gradual decline after 2045 due to anticipated constraints in nickel availability, as indicated by their system dynamics model simulations. In addition to supply chain-related concerns,

stainless steelmaking is associated with potential climate and environmental impacts. For example, Scope 3 greenhouse gas (GHG) emissions contribute substantially to the overall climate impact of stainless steel products, accounting for 59% of the total 1.95 tCO₂eq per ton stainless steel at an 85% scrap rate, 78% of the total 2.9 tCO₂eq per ton stainless steel at a 50% scrap rate, and 88% of the total 6.8 tCO₂eq per ton stainless steel at a 30% scrap rate [4].

Promoting resource-efficient and environmentally friendly stainless steel production requires enhanced recovery and reuse of valuable components from industrial residues. In recent years, much effort has been put into recovering valuable elements from slag and dust generated in stainless steelmaking. Previous studies have investigated metal recovery potentials in several contexts, such as (i) co-reduction processing of stainless steel dust [5], (ii) carbon-thermal direct reduction of CBSC (carbon-bearing composite briquette of stainless steel dust and chromium-containing slag) [6], and (iii) carbothermal reduction of metal particles from stainless steel dust [7]. Nevertheless, Holappa et al. [8] noted that only a small fraction of stainless steel slags is currently utilized in practice, with the majority still landfilled. Similarly, stainless steel dust and pickling sludge are mostly disposed of in landfills under current industrial practices [9].

Pickling sludge is another important waste stream due to its content of valuable components, including fluorspar (CaF₂) currently listed as a critical raw material in the European Union [10]. During stainless steel production, substantial volumes of metal hydroxide sludge are generated in the neutralization stage following the pickling process [11,12]. Pickling involves immersing stainless steel in an acidic solution to remove oxide scales and surface impurities, thereby preparing the material for subsequent processing or final use. The resulting sludge typically contains, among other components, fluorspar as well as chromium-, nickel-, and molybdenum-containing substances. The recovery and reuse of these secondary materials can reduce reliance on primary materials in stainless steelmaking and decrease the volume of pickling sludge sent to landfill.

Two main technological routes exist for resource recovery from pickling sludge, namely hydrometallurgical and pyrometallurgical techniques. In brief, hydrometallurgical techniques typically involve processes such as leaching, solvent extraction, and precipitation processes to selectively recover metals from sludge, often operating at relatively low temperatures while requiring chemical reagents and generating liquid residues [13,14]. In contrast, pyrometallurgical techniques rely on high-temperature treatment such as smelting or thermal processing to recover metals, which can handle complex feedstocks but are often energy-intensive and may involve emissions control challenges [15].

To support better environmental decision-making and foster more sustainable industrial practices, it is crucial to achieve a comprehensive understanding of the environmental implications associated with resource recovery from stainless steel pickling sludge. Life cycle assessment (LCA) is an internationally standardized methodology for evaluating the potential environmental impacts of products or services from a life cycle perspective [16,17]. So far, the body of literature on LCA of resource recovery pathways for industrial sludge remains limited. For example, Hu et al. [18] reported the carbon footprint of fluorspar recovered from waste calcium fluoride sludge in the electronics industry. Arguillarena et al. [19] assessed the resource use and environmental performance of alternative processes for zinc and iron recovery from spent pickling acid (SPA) generated in hot-dip galvanizing (HDG) industrial facilities. Similarly, Moreno-González et al. [20] analyzed the environmental impacts related to different management and valorization strategies for metal-rich sludge from the treatment of acid mine drainage (AMD). Despite this, previous studies address different types of sludge and industrial contexts and are therefore not directly comparable to stainless steel pickling sludge systems. To the best of our knowledge, no published

studies have systematically assessed the life cycle environmental impacts associated with both the recovery and reuse of resources from stainless steel pickling sludge.

To fill this knowledge gap, the present study conducts a comprehensive LCA of resource recovery from stainless steel pickling sludge and its subsequent reuse in argon oxygen decarburization (AOD) during stainless steelmaking, based on a real-world case study in Sweden. In this context, the recovered product (Hydrofluss) is obtained via thermal treatment of pickling sludge and contains CaF_2 and alloying elements, enabling its reuse in the AOD process. The primary objective is to assess how the climate and other environmental impacts of the AOD process change when using recovered secondary resources rather than conventional primary resources.

2. Materials and Methods

2.1. Case Description

This study examines the environmental impacts of a resource recovery and reuse system for stainless steel pickling sludge between two companies in Sweden, namely Outokumpu Stainless AB (Outokumpu, Avesta, Sweden) and Minpro Recycling AB (Minpro, Lindesberg, Sweden), forming an industrial symbiosis loop. Originating from the acid-based removal of oxide scale during cold rolling, pickling sludge is generated during the neutralization of spent acid and rinse water from stainless steel annealing and pickling (Figure 1). The dewatered sludge is referred to as hydroxide sludge (around 46–51% dry-solids content) and serves as the feedstock for the Minpro recovery process.

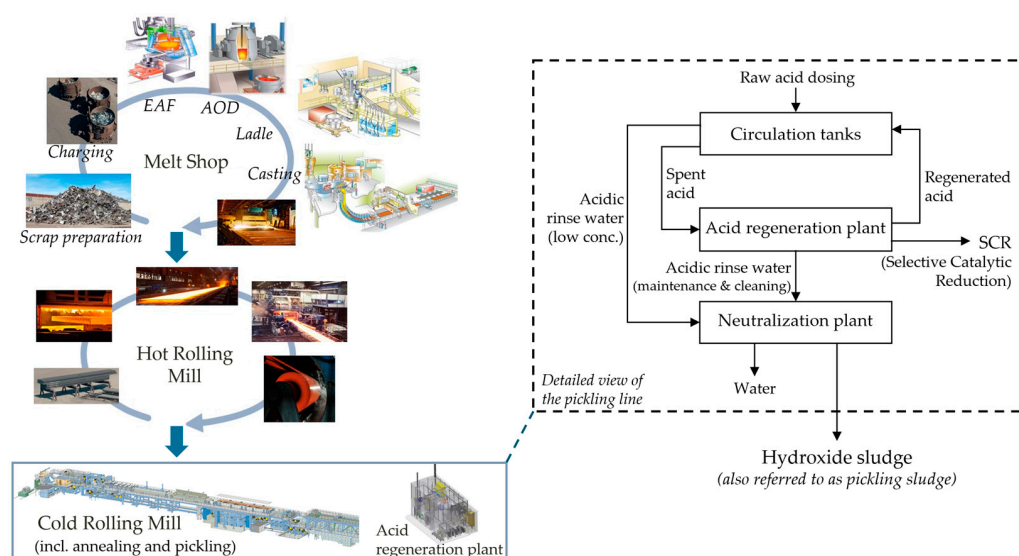


Figure 1. Overview of stainless steel production and pickling sludge generation.

At Minpro, the hydroxide sludge is thermally processed in a rotary kiln to convert the sludge mixture into more readily recoverable compounds (Table 1), including oxides of chromium (Cr), nickel (Ni), manganese (Mn) and molybdenum (Mo), as well as fluorspar. The rotary kiln is currently heated using light fuel oils, including the Swedish grades E10 (65%) and E32 (35%). The recovered product, referred to as Hydrofluss, is then transported back to Outokumpu and used in the AOD process. In the AOD process, Hydrofluss can partially offset the demand for nature fluorspar and ferroalloys produced from primary resources, including ferrochromium (FeCr), ferronickel (FeNi), ferromolybdenum (FeMo), and ferromanganese (FeMn).

Table 1. Average measured composition of valuable components in Hydrofluss.

Resource	Content (wt%, Dry Basis)
CaF ₂	50%
Fe	13%
Cr	5%
Ni	3%
Mn	0.5%
Mo	0.5%

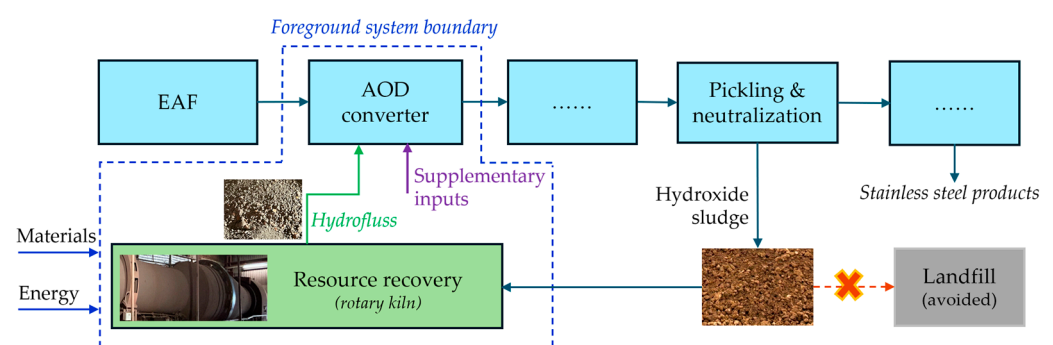
2.2. Life Cycle Assessment

2.2.1. Goal and Scope Definition

The goal of the LCA study was to assess the potential climate and other environmental impacts associated with Hydrofluss recovery from hydroxide sludge generated in stainless steel production and subsequent reuse in the AOD converter. The potential benefits of this resource recovery and reuse system were identified through comparison with a reference AOD process operating with primary materials.

The functional unit (FU) of the study was defined as 1 ton of recovered Hydrofluss delivered for use in the AOD converter at the Outokumpu plant in Avesta, Sweden. This FU ensures a consistent basis for quantifying its substitution of conventional materials under industrial operating conditions. The studied system is modelled using a cut-off allocation approach (consistent with ecoinvent system modelling) [21], in which the hydroxide sludge is treated as a waste stream from stainless steelmaking and enters the recovery subsystem without carrying upstream environmental burdens.

The system boundary of the study (Figure 2) was defined as “cradle-to-gate”; however, it includes the use of Hydrofluss within the AOD converter up to the point where its functional substitution of primary materials occurs. Due to the lack of detailed information on the composition of the original pickling solution (e.g., concentrations of hydrofluoric acid and nitric acid), the foreground system boundary was defined starting from the post-neutralization hydroxide sludge. This approach ensures consistency between the compared scenarios by setting the system boundary at the point where the sludge becomes available for recovery.

**Figure 2.** System boundary of the foreground processes included in the study.

Other stainless steelmaking processes, as well as downstream waste management activities were excluded, including sludge landfiling in the reference scenario and AOD slag disposal in the Hydrofluss scenario due to lack of data. Iron (Fe) was also excluded, since it is neither a limiting nor a high-value alloying element in stainless steelmaking and is already abundant in the AOD process. The exclusion of Fe is not expected to significantly affect the comparative results of the study, since its contribution to environmental impacts is relatively small compared with that of alloying elements such as Ni and Cr.

2.2.2. Life Cycle Inventory (LCI)

In the LCI phase, both industry-specific (“foreground”) and generic (“background”) inventory data were used. The industry-specific data included material and energy inputs related to (i) the Hydrofluss recovery process and (ii) the use of Hydrofluss in the AOD converter in stainless steel production, based on the industry-specific production data from 2024. No mass or economic allocation was applied to the Hydrofluss recovery process, since Hydrofluss is the only product of the process. Regarding the Hydrofluss recovery process, detailed primary data on process-specific emissions to air, water and solid waste streams were not available and were therefore not included in the LCI. As a result, the foreground inventory data in the present study primarily focus on material and energy inputs.

For the AOD converter, Hydrofluss is used as a substitute for 50% of the natural fluorspar used to ensure a fluid slag during the production of steel grade 304 (18/8 steel) and grade 316 (acid-resistant stainless steel). In addition to replacing natural fluorspar, Hydrofluss can partially substitute several ferroalloys produced from primary materials, including FeNi, FeCr, FeMo, and FeMn. However, supplementary inputs of ferrosilicon (FeSi) and lime (CaO) are required in the AOD process when Hydrofluss is used, to facilitate the reduction of chromium oxides, control slag chemistry, and enable sulphur removal.

The generic background LCI data used in this study were primarily sourced from the ecoinvent database v3.11 [21] within the SimaPro v10.3.0.1 software. An exception was the production of FeCr, for which a modified ecoinvent dataset was developed to better represent FeCr production conditions relevant to the European context. Based on the existing LCI dataset “Ferrochromium, high-carbon, 55% Cr {RoW} | ferrochromium production, high-carbon, 55% Cr | Cut-off, U”, the modification involved replacing the default RoW (“Rest-of-World”) inputs for hard coal, hard coal briquettes, and electricity with EU-wide supply mixes. This adjustment was made because the environmental impacts associated with upstream energy production vary substantially across regions, and the modified FeCr dataset provides a more representative European context for this study. Compared to the original FeCr production in ecoinvent, the modified FeCr production process resulted in a 22.3% reduction in the climate change impact (3.35 vs. 4.41 kg CO₂eq/kg) and an 8.7% reduction in the single score (608 vs. 666 µPt), based on the selected PEF method. The influence of assumptions related to FeCr production on the overall LCA results was further examined through sensitivity analysis (Sections 2.2.4 and 3.3), considering alternative LCI datasets representing different geographic production conditions.

2.2.3. Life Cycle Impact Assessment (LCIA)

The LCIA was performed using the Product Environmental Footprint (PEF) 3.1 method [22], implemented as “Environmental Footprint 3.1 (adapted), v1.04” in SimaPro v10.3.0.1. PEF is the LCIA method developed and recommended by the European Commission to measure and communicate the life cycle environmental performance of products in the EU [22].

This study covered all 16 PEF impact categories, including climate change (CC), ozone depletion (OD), human toxicity-cancer (HTC), human toxicity-non-cancer (HTNC), particulate matter (PM), ionizing radiation-human health (IRHH), photochemical ozone formation-human health (POF), acidification (AC), eutrophication-terrestrial (ET), eutrophication-freshwater (EF), eutrophication-marine (EM), ecotoxicity-freshwater (ETF), land use (LU), water use (WU), resource use-minerals and metals (RUMM) and resource use-fossils (RUF).

In the PEF method, both normalization and weighting are mandatory steps. The final weighted result is presented as a dimensionless single score in points (Pt), i.e., the sum of all impact categories based on the EU-recommended normalization and weighting factors (Table 2). The single score enables comparison across impact categories and serves as a

basis for the identification of the most-relevant impact categories, i.e., categories jointly accounting for at least 80% of the total score [22].

Table 2. The normalization and weighting factors in the PEF 3.1 method [23,24].

Impact Category	Normalisation Factor ¹		Weighting Factor (%)
	Value	Unit	
Climate change	7.55×10^3	kg CO ₂ eq/person	21.06
Acidification	55.6	mol H ⁺ eq/person	6.2
Ecotoxicity, freshwater	5.67×10^4	CTUe/person ²	1.92
Particulate matter	5.95×10^{-4}	disease incidences/person	8.96
Eutrophication, marine	19.5	kg N eq/person	2.96
Eutrophication, freshwater	1.61	kg P eq/person	2.8
Eutrophication, terrestrial	1.77×10^2	mol N eq/person	3.71
Human toxicity, cancer	1.73×10^{-5}	CTUh/person ³	2.13
Human toxicity, non-cancer	1.29×10^{-4}	CTUh/person	1.84
Ionizing radiation	4.22×10^3	kBq U-235 eq/person	5.01
Land use	8.19×10^5	Pt/person	7.94
Ozone depletion	5.23×10^{-2}	kg CFC-11 eq/person	6.31
Photochemical ozone formation	40.9	kg NMVOC eq/person	4.78
Resource use, fossils	6.5×10^4	MJ/person	8.32
Resource use, minerals and metals	6.36×10^{-2}	kg Sb eq/person	7.55
Water use	1.15×10^4	m ³ deprived water/person	8.51

¹ Reference year: 2010, based on a world population of 6.9×10^9 persons. ² CTUe: Comparative toxic unit for ecosystems. ³ CTUh: Comparative toxic unit for humans.

2.2.4. Scenario and Sensitivity Analysis

To assess the environmental implications of resources recovered from the pickling sludge and utilized in the AOD converter, two scenarios were defined for comparison. First, the “reference scenario” represents the conventional AOD operation without the use of Hydrofluss. In this case, the AOD converter relies entirely on natural fluorspar and ferroalloys (FeCr, FeNi, FeMo, and FeMn) produced from primary resources. This scenario reflects the traditional practice in the absence of recovery and reuse of pickling sludge. Second, the “Hydrofluss scenario” reflects the studied Hydrofluss recovery and reuse system, as described in Section 2.2.1.

To evaluate the robustness of the LCIA results, four sensitivity analyses (SA1–SA4) were conducted (Table 3). These sensitivity analyses examined the influences of key modelling assumptions, including the selection of climate data, the choice of background datasets for FeCr production, the use of HVO100 (100% hydrogenated vegetable oil) as an alternative energy carrier, and the application of different LCIA methods.

Table 3. Summary of the sensitivity analyses.

Sensitivity Analysis (SA)	Description
SA1: Selection of climate data	Use product-specific climate data for (i) FeCr from Outokumpu in Finland) and (ii) light fuel oils in the Swedish market
SA2: Choice of FeCr production locations (beyond Finland in SA1)	Use ecoinvent datasets representing alternative FeCr production in Kazakhstan (KZ), South Africa (ZA), and Rest-of-world (RoW) ¹
SA3: Alternative energy carrier	Replace fossil light fuel oils with renewable HVO100
SA4: LCIA method selection	Apply six alternative LCIA methods in addition to PEF

¹ KZ, ZA and RoW are location codes (countries or subdivisions) used in the ecoinvent database [25]; RoW depends on the scope of each dataset/activity [26].

3. Results

3.1. Life Cycle Inventory

Table 4 presents the foreground LCI results for the Hydrofluss and the reference scenarios, based on industry-specific annual average production data in 2024. On average, two tons of hydroxide sludge are required to produce one ton of Hydrofluss ready for delivery. In practice, 1 ton of Hydrofluss can replace approximately 0.5 ton of natural fluorspar in the AOD converter. According to Outokumpu's operational practice, secondary fluorspar can substitute up to 50% of the total fluorspar input while maintaining slag performance. In addition, the metal content of Hydrofluss enables partial substitution of the corresponding primary ferroalloys, as shown in the reference scenario.

Table 4. Life cycle inventory data for the two baseline scenarios, expressed per ton of Hydrofluss.

Baseline Case	Resource Inputs	Value	Unit
1. Hydrofluss scenario	Resource recovery		
	Hydroxide sludge	2.0 ¹	ton
	Slaked lime	0.005 ¹	ton
	Iron(II) sulphate	0.001 ¹	ton
	Electricity	30 ¹	kWh
	Light fuel oils	0.15 ¹	m ³
	Water	0.46 ¹	m ³
	Secondary resource use		
	Hydrofluss	1.0 ¹	ton
	Ferrosilicon	0.10 ¹	ton
	Quicklime	0.15 ¹	ton
2. Reference scenario	Primary resource use		
	Ferronickel (25% Ni) ²	0.12 ³	ton
	Ferrochromium (55% Cr) ²	0.09 ³	ton
	Ferromolybdenum (67% Mo) ²	0.004 ³	ton
	Ferromanganese (74.5% Mn) ²	0.007 ³	ton
	Natural fluorspar (97% CaF ₂) ²	0.5 ³	ton

¹ Average industry-specific production data collected in the present case study. ² Elemental proportions obtained from existing background LCI datasets in SimaPro. ³ Estimated amounts of primary materials substituted by 1 ton of Hydrofluss.

The values in the reference scenario represent the quantities of primary materials required to achieve comparable metallurgical performance in the absence of Hydrofluss. These quantities were estimated based on the elemental mass fractions of the elements/components in Hydrofluss (Table 1) and the corresponding concentrations of commercial ferroalloy products (Table 4). These avoided material flows in the reference scenario, together with the additional material and energy inputs required in the studied system, form the basis for assessing the potential environmental benefits associated with Hydrofluss recovery and utilization.

3.2. Life Cycle Impact Assessment

The comparative life cycle environmental impact results for the reference and Hydrofluss scenarios are illustrated in Figure 3 and Tables S1 and S2 in Supplementary Materials. The total climate impacts of the reference scenario and Hydrofluss scenario were 1.51 and 1.42 tons CO₂eq/ton Hydrofluss, respectively. Overall, using 1 ton of recovered Hydrofluss in the AOD converter led to a potential reduction of 91.6 kg CO₂eq emissions (Scope 1–3), corresponding to a 6% decrease, compared to the reference scenario. Relative to the reference scenario, the Hydrofluss scenario showed higher impacts in five environmental categories (PM, IRHH, OD, RUF, and WU) and lower impacts in the other eleven categories (see Figure 3a).

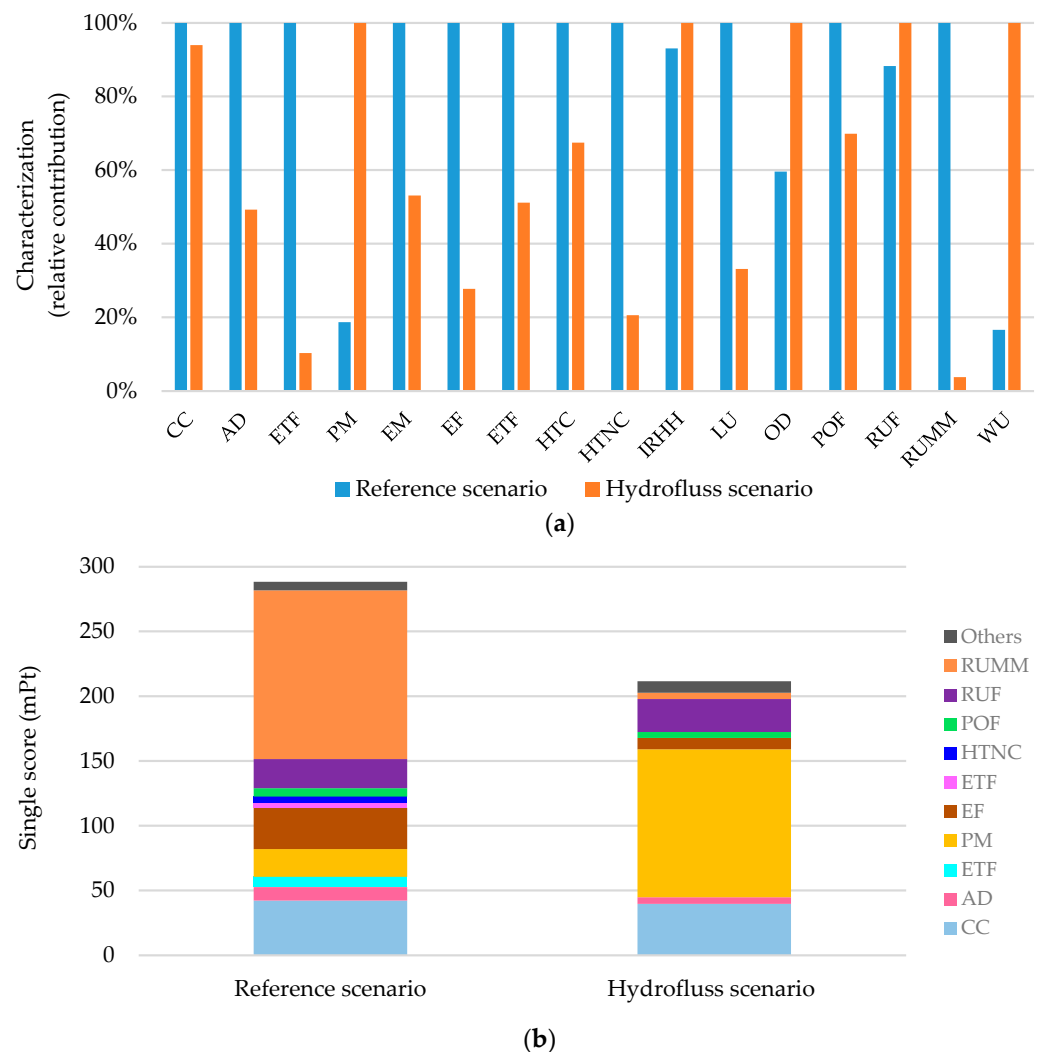


Figure 3. Comparative LCIA result for the reference and Hydrofluss scenarios: (a) characterization; (b) single score, based on the “Environmental Footprint 3.1 (adapted) v1.04” method and ecoinvent v3.11 in SimaPro v10.3.0.1. The term “Others” refers to the sum of environmental impact categories, each contributing less than 1% of the total single score for each scenario.

In the Hydrofluss scenario, the supplementary FeSi input to the AOD converter was the largest contributor to the climate change impact (47.9%), followed by the Hydrofluss recovery process (39.7%) and the supplementary CaO input to the AOD converter (12.4%). With respect to the Hydrofluss recovery process, the total climate impact was 0.56 ton CO₂eq/ton Hydrofluss, dominated by emissions from the use of light fuel oils (93.8%) in the rotary kiln. In the reference scenario, the total climate impact was 1.51 tons CO₂eq from natural fluorspar and primary ferroalloys equivalent to the corresponding content per ton Hydrofluss, with the largest contributor from FeNi (67.8%), followed by FeCr (20.3%), fluorspar (8.7%), FeMo (2.0%), and FeMn (1.2%).

The single score results (Figure 3b and Table 5) showed that the Hydrofluss scenario exhibited superior overall environmental performance compared with the reference scenario. The Hydrofluss scenario achieved a single score of 211.6 mPt (millipoint), corresponding to 26.6% reduction relative to the reference scenario’s value of 288.3 mPt (Table S3 in Supplementary Materials). In the reference scenario, the main contributors were FeNi (44.2%), FeMo (29.3%), FeCr (19.3%), and fluorspar (6.6%). The identified five most-relevant impact categories were (i) resource use, minerals and metals (45.1%), (ii) climate change (14.7%), (iii) eutrophication, freshwater (11.0%), (iv) resource use, fossils (7.8%), and (v)

particular matter (7.4%). For the Hydrofluss scenario, the dominant contributor was the supplementary input of FeSi (81.8%), while its most-relevant impact categories included (i) particulate matter (54.0%), (ii) climate change (18.8%), and (iii) resource use—fossils (12.0%).

Table 5. Percent contribution (%) of impact categories to the single score results.

Impact Category	Reference Scenario						Hydrofluss Scenario			
	FeCr	FeMn	FeMo	FeNi	CaF ₂	Total	Hydrofluss	CaO	FeSi	Total
CC	3.0	0.2	0.3	9.9	1.3	14.6 ¹	7.4	2.3	9.0	18.8 ²
AD	0.4	0.06	0.09	2.6	0.4	3.6	0.6	0.1	1.7	2.4
ETF	0.1	0.02	0.02	2.6	0.1	2.8	0.05	0.01	0.34	0.4
PM	0.3	0.08	0.3	5.6	1.1	7.4 ¹	0.66	0.06	53.26	54.0 ²
EM	0.1	0.02	0.03	0.6	0.1	0.9	0.16	0.03	0.45	0.6
EF	1.0	0.06	0.00	9.6	0.3	11.0 ¹	0.07	0.01	4.09	4.2
ETF	0.1	0.03	0.04	0.9	0.2	1.3	0.24	0.04	0.60	0.9
HTC	0.2	0.07	0.04	0.2	0.0	0.6	0.09	0.001	0.45	0.5
HTNC	0.0	0.01	0.01	1.6	0.2	1.8	0.10	0.01	0.39	0.5
IRHH	0.2	0.01	0.01	0.2	0.03	0.5	0.08	0.01	0.61	0.7
LU	0.03	0.004	0.001	0.3	0.04	0.3	0.04	0.004	0.10	0.1
OD	0.0008	0.00004	0.00001	0.003	0.001	0.005	0.01	0.001	0.004	0.01
POF	0.3	0.05	0.06	1.5	0.3	2.2	0.86	0.13	1.14	2.1
RUF	1.7	0.09	0.14	5.1	0.7	7.8 ¹	4.44	0.45	7.16	12.0 ²
RUMM	11.6	0.02	28.16	3.7	1.7	45.1 ¹	0.15	0.02	2.13	2.3
WU	0.1	0.01	0.07	−0.1 ³	0.04	0.1	0.10	0.00	0.31	0.4
Total	19.3	0.7	29.2	44.2	6.5	100	15.1	3.2	81.8	100

¹ Identified as the most-relevant impact categories in the reference scenario. ² Identified as the most-relevant impact categories in the Hydrofluss scenario. ³ The negative water use value is due to the modelling approach applied for run-of-river hydropower production in ecoinvent v3, in which water returns to rivers (outputs) receives a negative characterization factor and is therefore treated as negative water consumption [27,28].

3.3. Sensitivity Analysis

Table 6 presents the parameter values used in the sensitivity analyses of the reference and Hydrofluss scenarios, complementing the brief summary in Table 3. In fact, the two parameters selected for SA1 represent the primary sources of climate data for FeCr and light fuel oils in the context of the present study. These product-specific climate data were not used in the reference and Hydrofluss scenarios because their underlying background LCI datasets are not publicly available, which prevented their integration into the multi-impact category LCA framework for the two baseline scenarios in this study. The variation in climate impacts among FeCr production regions is primarily driven by differences in national electricity mixes, as well as direct process emissions from carbon-based reductants and variations in process efficiencies. With respect to SA4, the technical feasibility of fully substituting light fuel oils with HVO100 as heating fuel has been confirmed by a major fuel supplier in the Swedish market [29].

Table 6. Summary of parameters and values used in the baseline and sensitivity analyses.

Case	Parameter	Unit	Reference Scenario	Hydrofluss Scenario
Baseline	FeCr (55% Cr), climate data ¹	kg CO ₂ eq/kg	3.35	–
	Light fuel oils (LFO), climate data ¹	kg CO ₂ eq/MJ	–	0.10
	Heating oil (LFO)	m ³ /ton Hydrofluss	–	0.15
SA1: Climate data	FeCr (52.5% Cr): EPD (Outokumpu, Finland) ²	kg CO ₂ eq/kg	1.75	–
	LFO: Market-specific (Sweden) ³	kg CO ₂ eq/MJ	–	0.07

Table 6. Cont.

Case	Parameter	Unit	Reference Scenario	Hydrofluss Scenario
SA2: FeCr production (ecoinvent datasets)	FeCr (68% Cr, Kazakhstan) ¹	kg CO ₂ eq/kg	5.82	–
	FeCr (55% Cr, South Africa) ¹	kg CO ₂ eq/kg	5.74	–
	FeCr (55% Cr, Rest-of-World) ¹	kg CO ₂ eq/kg	4.31	–
SA3: Energy carrier	HVO100 (fully replacing LFO) ⁴	m ³ /ton Hydrofluss	–	0.16

¹ Calculated using “Environmental Footprint 3.1 (adapted), v1.04” in SimaPro v10.3.0.1. ² Data source: Outokumpu (2023) [30]. ³ Data source: Preem (2022) [31,32]. ⁴ Based on the lower heat value of LFO (42.9 MJ/kg) [31,32] and HVO100 (43.7 MJ/kg) [29].

Table 7 presents the variation in climate impact between the reference and Hydrofluss scenarios across the first four sensitivity analyses SA1–SA4. Relative to the baseline, SA1 resulted in lower climate impacts for both the reference and Hydrofluss scenarios, while its total CO₂eq reduction potential (−91.8 kg CO₂eq) was almost identical to that of the baseline (−91.6 kg CO₂eq). In SA2.1–2.3, the assumed geographic variation in FeCr production led to approximately 1.9–3.4 times greater climate benefits than in the baseline scenario. Regarding the LCI of SA2, the quantity of each alternative FeCr product with varying chromium content was determined based on chromium equivalence. In SA3, the substitution of light fuel oils with HVO100 can substantially reduce the climate impact of the Hydrofluss scenario, resulting in a decrease of 540.3 kg CO₂eq per ton of Hydrofluss.

Table 7. Sensitivity analysis (SA1–SA3) of the climate impact (kg CO₂eq/ton Hydrofluss) for the reference and Hydrofluss scenarios.

Case	Reference Scenario	Hydrofluss Scenario	Change in Climate Impact *
Baseline	1514.9	1423.3	−91.6
SA1 (Product-specific climate data)	1376.8	1285.0	−91.8
SA2.1 (FeCr production: Kazakhstan)	1637.5	1423.2	−214.3
SA2.2 (FeCr production: South Africa)	1731.7	1423.2	−308.5
SA2.3 (FeCr production: Rest-of-World)	1601.4	1423.2	−178.2
SA3 (HVO100 substituting LFO)	1514.9	974.6	−540.3

* Calculated as the value of the Hydrofluss scenario minus that of the reference scenario.

Regarding SA4, Figure 4 illustrates the climate change impact of the reference and Hydrofluss scenarios using seven alternative LCIA methods [33] implemented in SimaPro v10.3.0.1. Compared to the reference scenario based on the “Environmental Footprint 3.1 v1.04” method, the use of other LCIA methods resulted in a difference between −1.1% and 1.5%, namely TRACI 2.2 v1.01 (−1.1%), CML-IA baseline v3.12 (−0.4%), IPCC 2021 GWP100 v1.03 (−0.003%), IMPACT World+ Midpoint v2.00 (+0.2%), EN 15804 + A2 v1.04 (+1.3%), and ReCiPe 2016 Midpoint (H) v1.12 (+1.5%). A similar result was observed for the Hydrofluss scenario using those alternative LCIA methods.

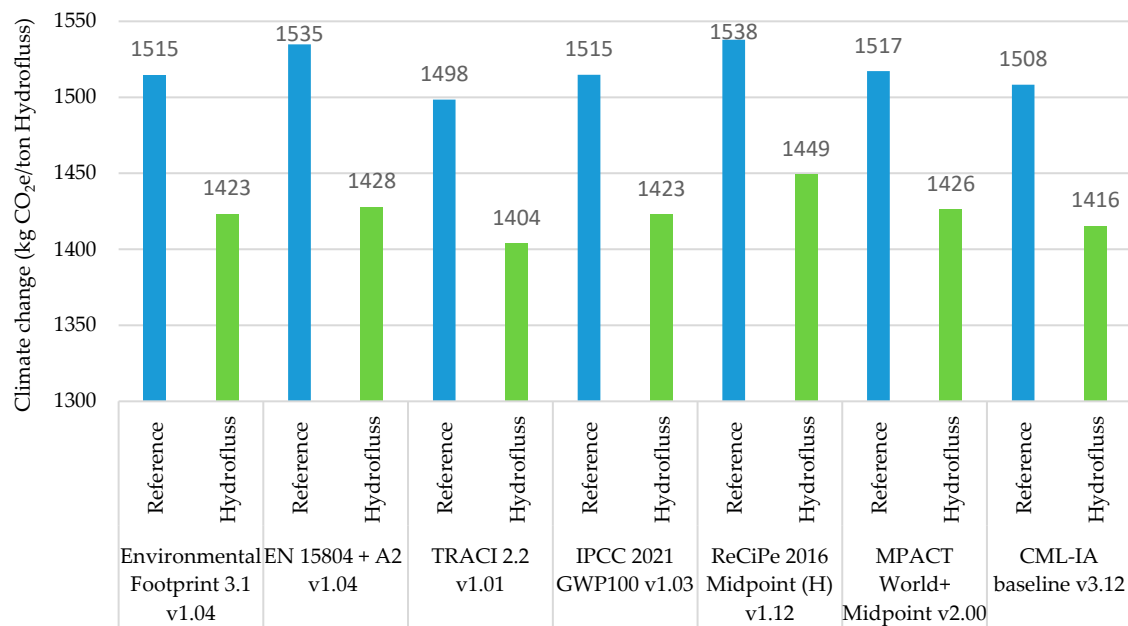


Figure 4. Climate change in the reference and Hydrofluss scenarios using seven different impact assessment methods in SimaPro v10.3.0.1.

4. Discussion

This study presents the first comprehensive multi-impact category LCA involving both the recovery and subsequent use of valuable resources derived from stainless steel pickling sludge. Based on a Swedish industrial case and site-specific production data, the LCA results show that valorizing the recovered secondary resources in the AOD process (“Hydrofluss scenario”) yields a net climate benefit, compared with the conventional system relying on primary ferroalloys and natural fluorspar (“reference scenario”). Specifically, the use of 1 ton of the recovered Hydrofluss product reduces the total climate change impact by 6% (91.6 kg CO₂eq). This net climate benefit is primarily owing to the avoided demand of energy- and carbon-intensive FeNi and FeCr from primary resources [34]. In a broader context, these findings align with previous research demonstrating that metal recovery and valorization pathways can potentially achieve lower climate and environmental impacts than primary production within metallurgical value chains [19,35].

The sensitivity analysis results (Table 7) highlight that the choice of FeCr products and energy carriers has a significant influence on the comparative climate and environmental performance of the studied scenarios. In SA1, the use of product-specific climate data for FeCr produced at Outokumpu in Finland (1.75 kg CO₂eq/kg) and for light fuel oils sold in the Swedish market (0.07 kg CO₂eq/MJ) resulted in approximately 10% lower absolute climate impacts for both scenarios, while the relative difference remained largely unchanged compared with the baseline. In contrast, the results of SA2 demonstrate a strong dependence on the geographic origin of FeCr production. Using alternative ecoinvent LCI datasets for FeCr production in Kazakhstan (5.82 kg CO₂eq/kg), South Africa (5.74 kg CO₂eq/kg), and the Rest-of-World (4.31 kg CO₂eq/kg) led to substantial variations in climate impact reduction potentials, ranging from 178.2 to 308.5 kg CO₂eq/ton Hydrofluss. This finding underscores the strong influences of upstream FeCr production conditions on the overall LCA results. In practice, the environmental impacts of ferroalloy production and associated energy supply systems vary significantly across regions. As a result, the environmental performance of the Hydrofluss system is context-dependent and may vary depending on the sourcing of FeCr across different industrial and geographic contexts.

Similarly, the results of SA3 show that the choice of energy carriers in the resource recovery system plays a key role in overall environmental performance. As shown in Table 7, replacing fossil-based heating oils with renewable HVO100 could increase the climate benefit of the studied system by a factor of six (540.3 kg CO₂eq/ton Hydrofluss) compared with the baseline scenario. While the transition to a bio-based renewable heating oil in practice also depends on the economic feasibility of the resource recovery process, the associated high potential for Scope 3 emission reductions represents a key driver for enabling broader valorization of recovered resources in stainless steelmaking. Overall, the sensitivity analysis indicates the importance of considering regional and supply chain variability when interpreting the LCA results and when transferring the findings of this study to other industrial contexts.

In the current LCA of the reference and Hydrofluss scenarios, several modelling limitations should be noted. First, due to the lack of industry-specific operational data, as mentioned in Section 2.2.1, certain upstream and downstream processes were excluded. For example, the composition of the pickling solution and detailed neutralization parameters were not modelled. However, this is not expected to affect the validity of the comparative LCA results, as both scenarios are modelled from the same starting point (i.e., hydroxide sludge generated after neutralization). Second, the substitution of primary materials (Table 4) is based on industrial operational data and elemental composition, representing a first-order approximation of material equivalence. Potential differences in metallurgical performance, process efficiency, and recovery yields are not modelled due to data limitations. Third, two onsite waste treatment processes were excluded, namely (i) landfilling of pickling sludge in the reference scenario, and (ii) management of additional slag (0.25 ton per ton of Hydrofluss) generated in the AOD process in the Hydrofluss scenario. Including the former would likely increase the overall climate impact of the reference scenario, thereby strengthening the relative climate benefit of the Hydrofluss scenario. For the latter, the AOD slag is conventionally landfilled without cement-based stabilization, and no representative LCI datasets were available in ecoinvent v3.11 or in the literature at the time of this study. Finally, additional parameters, such as transport distances, substitution ratios (primary vs. secondary materials), and resource recovery efficiency of sludge, were not included in the sensitivity analysis. These parameters may influence the LCA results and should therefore be interpreted with caution.

To obtain an approximate estimation of the climate impact of landfilling AOD slag, two existing LCI datasets in ecoinvent v3.11 were modified (i.e., by removing cement use) and used as proxies: (i) “Basic oxygen furnace slag [GLO] | treatment of basic oxygen furnace slag, residual material landfill | Cut-off, U”, and (ii) “Basic oxygen furnace waste [RER] | treatment of basic oxygen furnace waste, residual material landfill | Cut-off, U”. Using the PEF v3.1 method in SimaPro v10.3.0.1, the calculated climate impacts for the two modified landfilling scenarios were 3.53 and 3.25 kg CO₂eq per ton of Hydrofluss, respectively (Table S4 in Supplementary Materials). These results indicate that the exclusion of the two onsite waste treatment processes is unlikely to affect the overall conclusion in Section 3 that the Hydrofluss scenario delivers a net climate benefit. However, on-site land availability remains a potential limitation for landfilling. It is also worth noting that previous studies have explored potential alternative valorizing pathways for AOD slag, such as its use as an aggregate in road construction [8,36], although these options fall outside the scope of the present study.

Beyond climate change, this study highlights the need for multi-impact LCAs to enable a more holistic understanding of the environmental implications associated with resource recovery and utilization systems. This reflects the well-established need in LCA to avoid environmental trade-offs and burden shifting across environmental categories and life cycle

phases [37–40]. On the one hand, the weighted single-score results of the study (Table 5) show that the climate change category contributes only 14.6% of the total single score in the reference scenario and 18.8% in the Hydrofluss scenario. In the reference scenario, for instance, the largest contributor is the impact category “resource use-minerals and metals (RUMM)”, accounting for 45.1% of the total single score. On the other hand, the Hydrofluss scenario exhibits higher impacts in five environmental categories (Figure 3), namely particulate matter (PM), ionizing radiation-human health (IRHH), ozone depletion (OD), resource use-fossils (RUF), and water use (WU). These trade-offs are mainly associated with energy use in the Hydrofluss recovery process and the additional material inputs required in the AOD converter, particularly FeSi. This highlights the importance of explicitly addressing potential burden-shifting when evaluating the environmental performance of circular resource systems.

From an environmental sustainability perspective, comprehensive LCA studies should address not only climate change but also other environmental impact categories [41]. Laurent et al. [42] demonstrated a weak correlation between carbon footprint (CF) and several environmental impact categories, such as resource depletion and land use, indicating that CF alone is a poor proxy for overall environmental performance of products. Even so, product carbon footprint (PCF) remains the only environmental impact category proposed by the Joint Research Centre of the European Commission [43] for inclusion in the Digital Product Passport (DPP) for iron and steel products, including stainless steel, under the Ecodesign for Sustainable Products Regulation (ESPR). This underscores the need for broader discussion and consensus on the necessity and practical feasibility of integrated environmental sustainability assessment across metals and minerals value chains, beyond the prevailing focus on carbon footprints.

Methodologically, several challenges arise when applying LCA to circular economy systems. These include the treatment of waste/by-products/co-products, allocation choices, system boundary definitions, and the handling of avoided burdens. Different system models (such as cut-off, substitution, and consequential) [21,44], as well as different LCIA methods [45], can lead to divergent conclusions regarding environmental benefits. These methodological choices should therefore be explicitly considered and transparently reported when designing LCA studies, interpreting results, and comparing findings across studies.

The Hydrofluss system offers several sustainability advantages, including reduced reliance on critical raw materials (e.g., fluorspar), lower overall environmental impacts, and alignment with circular economy principles. However, potential limitations include the complexity of the resource recovery process and its sensitivity to the choice of energy carriers. Opportunities include further emission reductions through the use of renewable energy sources (as demonstrated in Table 7) and increased regulatory support for circular materials. Potential threats include volatility in ferroalloy markets and regulatory uncertainties, particularly regarding policy incentives, carbon pricing, and permitting processes for new recovery plants across different regions. Although this study focuses on life cycle environmental performance, the economic feasibility of the Hydrofluss recovery and reuse business model is also a key factor for large-scale implementation. Potential challenges include economic competitiveness relative to market prices of ferroalloys, dependency on energy costs, and capital investment for scaling recovery facilities.

5. Conclusions

The findings of this Swedish case study indicate that the recovery of valuable resources (Hydrofluss) from pickling sludge and their reuse in stainless steelmaking can lead to overall climate and environmental benefits. Compared with the reference scenario relying on primary materials in the AOD process of stainless steelmaking, the results show that

the valorization of Hydrofluss can reduce the climate change impact by 91.6 to 540.3 kg CO₂eq/ton, depending on the energy sources used in the resource recovery process. Furthermore, the results show that the Hydrofluss scenario performs better in 11 out of the 16 Product Environmental Footprint (PEF) impact categories, achieving a 26.6% reduction in the weighted single score. This highlights the importance of applying a multi-impact life cycle approach to identify potential environmental trade-offs and avoid burden shifting at the system level. In addition, the industry-specific production data reported in the life cycle inventory (LCI) analysis can serve as a basis for future LCA studies on stainless steelmaking, particularly for benchmarking resource recovery and reuse pathways for pickling sludge.

Future work should extend the present environmental LCA towards a more comprehensive life cycle sustainability assessment (LCSA) approach [46]. First, the system boundary should be expanded to cover the entire stainless steelmaking process, enabling assessment of how Hydrofluss used in the AOD converter contributes to the overall climate and environmental footprint of stainless steel products. Here, more industry-specific data, especially onsite emissions and waste streams, should be collected and incorporated into the LCA. Second, complementary economic and social dimensions should be included, for example, through techno-economic analysis (TEA), life cycle costing (LCC), and social life cycle assessment (S-LCA). This would provide a basis for evaluating the financial feasibility, social impacts, and stakeholder perceptions associated with Hydrofluss recovery and utilization. Results from such an LCSA framework can better support informed decision-making and facilitate the upscaling and implementation of circular business models in the stainless steel industry.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/cleantechnol8040107/s1>. Table S1: LCIA (characterization) results of the Hydrofluss and reference baseline scenarios, reported per ton of Hydrofluss; Table S2: LCIA (characterization, relative contribution) results of the Hydrofluss and reference baseline scenarios, reported per ton of Hydrofluss; Table S3: LCIA (single score) results of the Hydrofluss and reference baseline scenarios, reported per ton of Hydrofluss; Table S4: LCIA (characterization) results for landfilling of 1 ton of basic oxygen furnace slag and waste, based on the Product Environmental Footprint v3.1 method and ecoinvent v3.11 in SimaPro v10.3.01.

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Abbreviations

The following abbreviations are used in this manuscript:

AOD	Argon oxygen decarburization
CO ₂ eq	Carbon dioxide equivalent
EAF	Electric arc furnace
FU	Functional unit
GHG	Greenhouse gas
HVO	Hydrogenated vegetable oil
LFO	Light fuel oils
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
mPt	Millipoint
PEF	Product environmental footprint
RoW	Rest-of-World

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