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Industrial Recycling of Silicon-Containing Materials: From kg scale tests to large scale operation

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Abstract - The transition towards lower carbon footprint silicon value chains requires increased utilisation of secondary raw materials across multiple process steps. This work addresses this challenge by developing and demonstrating industrial pathways for recycling silicon-containing materials at Elkem Kristiansand. Two complementary activities are presented.
First, ferrosilicon- and silicon-rich skulls and slags from metallurgical ferrosilicon and silicon production are evaluated as supplementary cementitious materials, partially replacing clinker in cement applications. Material characterisation, processing routes, and performance testing demonstrate the potential for CO_2 reduction.
The activity covers remelting of silicon-rich skulls and slags to recover two distinct product streams: FeSi and a refined slag fraction. Process control focused on stable melting conditions, phase separation, and compositional consistency. Material quality was monitored through chemical analysis and particle-size control, enabling evaluation of both FeSi and slag for downstream cement applications.

Second, recycled silicon from wafer-sawing kerf is upgraded through purification, pellet production, melting, and casting into Si99 grades. Pilot- and industrial-scale trials confirm that recycled silicon can be transformed into consistent, high-quality products suitable for demanding downstream applications. Together, these results demonstrate how integrated recycling solutions can strengthen circularity and sustainability in the silicon industry. An integrated purification–pelletisation approach was developed to stabilise kerf properties, control organic and oxide behaviour, and produce mechanically robust pellets with predictable performance during subsequent melting. Si99 is produced by remelting kerf-based pellets under controlled furnace conditions. Pellet quality, charge composition, and ramp-up strategy are key process parameters. Stable melting, controlled slag formation, and ladle refining enable consistent chemistry prior to casting. Systematic sampling and online analysis are applied to verify yield, impurity levels, and product stability.

Elkem will in this work present operational data and results from large-scale campaigns at the Fiskaa site in Kristiansand, demonstrating process stability, material quality, and practical feasibility under industrial conditions.

1. INTRODUCTION

The metallurgical silicon industry is increasingly focused on improving resource efficiency and reducing the overall CO_2 footprint of its operations. One potential pathway to achieve this is the recycling of silicon-containing materials, including process residues, off-spec products, and side streams from downstream processing.
Recycling of silicon materials has been successfully demonstrated at laboratory scale (Syvertsen et al., 2018); however, the transition from controlled kg-scale tests to stable industrial operation introduces significant challenges. In particular, recycled materials such as kerf exhibit substantial variability in composition, including organic content, oxide phases, and metallic contaminants. This variability directly affects process stability, product quality, and overall system efficiency.

It is important to distinguish between carbothermic silicon production and remelting-based recycling. Carbothermic silicon production in a reduction furnace is based on the chemical reduction of SiO_2 using carbon, resulting in direct CO_2 emissions (Scope 1). In contrast,

recycling or remelting in an induction furnace is a purely electric process without direct CO_2 generation, where energy is supplied via electricity. Consequently, the CO_2 footprint of induction furnace operation is dominated by indirect emissions (Scope 2 and 3)
.
This paper will look closer at some aspects related to the transition from kg-scale recycling tests to industrial-scale operation. The impact of recycled material quality and variation on process and product will be evaluated, in addition to the CO_2 implications.

The present article is structured around the challenges related to scaling up to an industrial scale for two cases. The first route addresses recycling of kerf. Kerf supplied in a form of silicon filter cake is a side stream from cutting blocks and wafers in the solar industry (Emil-Kaya et al., 2025). Kerf is converted into pellets and further processed into metallurgical grade silicon (MG-Si). The second route, Slag2Value, focuses on remelting of FeSi slags and skulls to recover FeSi and produce a slag suitable to be used as a replacement for cement. This is one alternative for reducing cement content in order to reach a more sustainable concrete (Jhatial et al., 2023).

Elkem has developed these recycle cases in several R&D projects as indicated in figure 1. In 2025 the development went into a new phase, transferring the processes from lab to industrial scale in an Innovation Norway supported project.

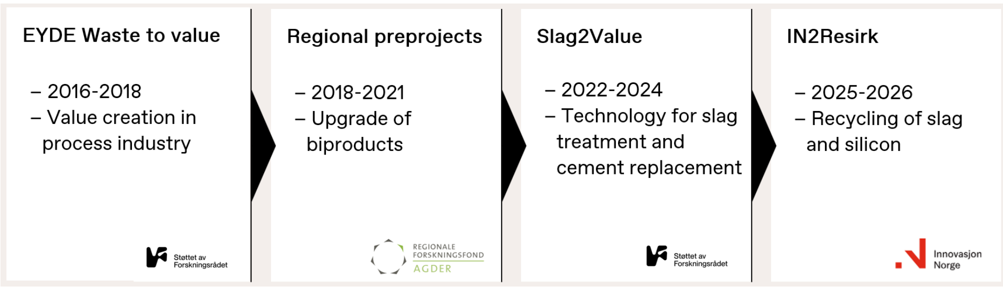

Figure 1: Time line for the development of industrial routes demonstrated at Fiskaa

The emphasis is not only on technical feasibility, but also on the challenges when a concept moves from lab or pilot scale into extended industrial campaigns. Elkem shares some of the gained experience within the area of raw-material stability and safety related to the development.

2. EXPERIMENTAL – TEST INFRASTRUCTURE

2.1 Industrial infrastructure at Fiskaa

The Elkem facilities at Fiskaa Kristiansand provide an unusual combination of equipment relevant for industrial recycling of silicon-containing materials. For the work reported here, the most relevant assets are the pellets plant, the multipurpose melting plant, the crushing/sieving/packing plant, the slag furnace and the analytical laboratory.

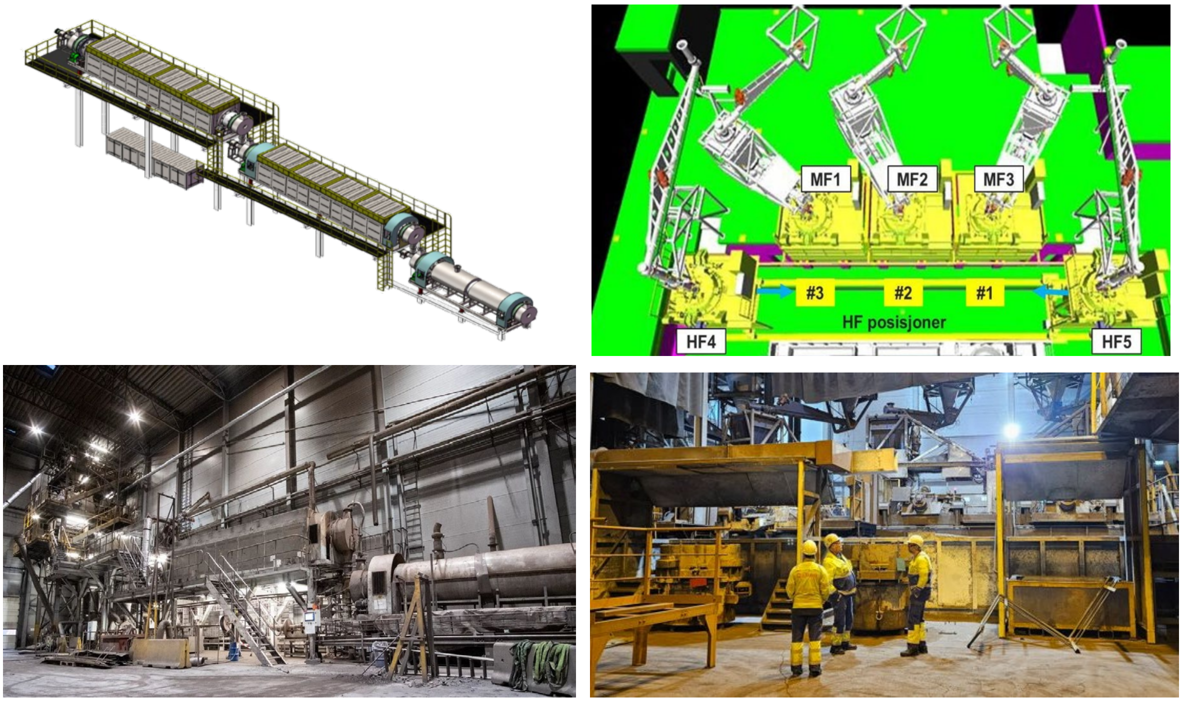

Figure 2: Layout and picture of the pellet and melting plant and at Elkem facilities at Fiskaa, Kristiansand.

Table I: A brief overview of test infrastructure in Kristiansand used in the campaigns

Unit / asset	Key role in this study
Pellets plant	Agglomeration, drying, calcination and cooling of kerf
Multipurpose melting plant	Batch melting, slag removal, transfer to holding furnace and ladle refining
Crushing and sieving plant (CSP)	Final sizing and packing of Si products
Analytical laboratory	Routine process and product control

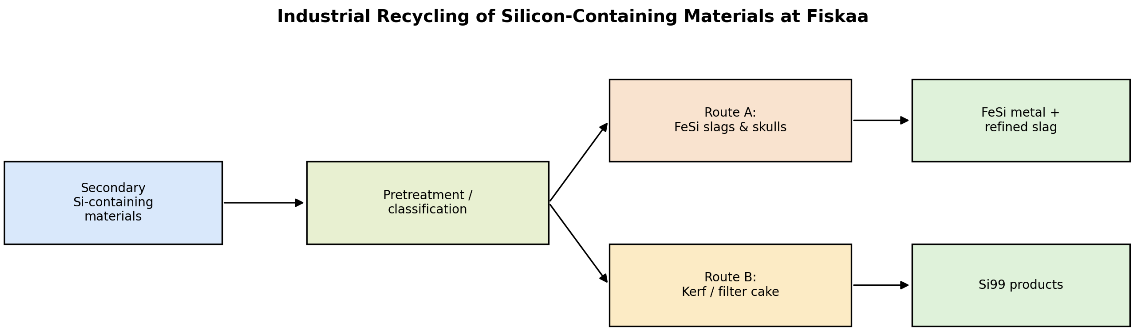

Figure 3: Schematic representation of the two industrial recycling routes demonstrated at Fiskaa

2.2 Route A – kerf upgrading to MG-Si

The kerf route starts with wet filter cake from wafer cutting and uses pelletisation as a controlled pre-treatment step before melting. The pellets line includes mixing/granulation in an Eirich mixer, drying, calcination under controlled atmosphere, off-gas treatment in an afterburner, and cooling. The pellets are then melted in induction furnaces, cast and crushed to customer size specifications.

Figure 4: Suggested route figure for kerf upgrading to Si99 via pellets, melting, crushing, sizing and packing (CSP)

2.3 Route B – recycling of FeSi slags and sculls

In the remelting route, FeSi slags and sculls are blended with Si-rich adjustment material and CaO in order to reach a process window that supports separation into a FeSi fraction and a lower-Si slag fraction. Earlier pilot and concept work identified basicity (CaO/SiO_2), settling time and slag thickness as controlling variables. For rapid cooling of the slag product, thin casting and/or quenching are used before milling.

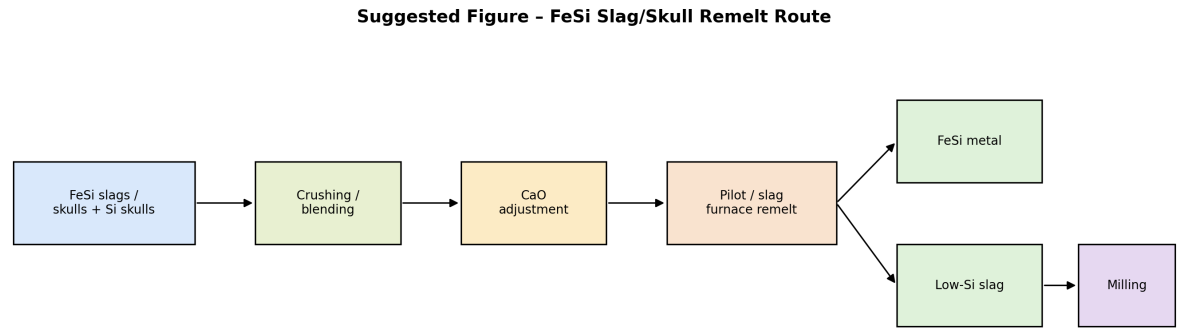

Figure 5: Suggested route figure for FeSi slag/skull remelting and downstream slag milling

2.4 QA and analytical framework

For the pellets and melt line, traceability and online process monitoring were performed through an operational process control system (Predictor). The monitored variables included ID, raw-material properties, process parameters and product quality. Product control was carried out with several different measuring techniques (eg. LECO, XRF, XRD, SEM, etc).

Figure 6: Example of analytical tools used during large scale campaign - Autolab

3. RESULTS & DISCUSSION

3.1 Kerf quality and its impact on pelletisation

Elkem has observed that there is variation in the raw material as indicated in table 2.

Table II: Examples of variation in raw material based on kerf

Parameter	Typical range	Comment
Organic content	1–4 wt%	Originating from cutting fluids / binders
Oxygen content	2–7 wt%	Surface of primary Si particle and organic compounds
Metallic contaminants	0.1–1 wt%	Foreign fragments (wire, bolts, nuts, etc)
Magnetic fraction	Variable	Recoverable
Non-magnetic fraction	Present	Remains in process
Base material	Poly-Si based	Low Fe (sub-ppmw level)

The recycled kerf material shows significant variability in composition, particularly in organic content (~1–4 wt%), oxygen level (~2-7 wt%) and the presence of metallic contaminants originating from mechanical equipment (e.g. wires, bolts, liners, and structural components). While part of the metallic fraction can be removed through magnetic separation and sieving, a non-negligible fraction remains and enters the melting process.

Non-metallic and metallic contaminants that are not removed prior to processing are dissolved into the melt during melting, directly contributing to elevated impurity levels in the final silicon product. Findings from the test campaign with more than 100 MT demonstrate a large range of contaminants, and Figure 7 shows some of the fragments that were identified and removed.

Figure 7: Pictures showing samples of fragments found in the kerf raw material. Scale approximately 1–5 cm.

3.2 Scale-up: industrial campaign on recycling Si

Elkem has selected some key elements in order to follow the material quality through the process steps. For the recycling of Si the focus has been on phosphorus (P) and iron (Fe) as important elements both for process control and as final quality indicator. In addition, carbon, oxygen and humidity are critical elements for the raw materials both for pellets and melting process.

Table III gives an overview of the different steps and observed minimum and maximum values for C, O, humidity, Fe and P. The data are from the large-scale testing carried out at Fiskaa, Kristiansand.

Table III: Overview of key quality indicators for the individual process steps, showing the content and variation of central elements compared with typical values for metallurgical-grade silicon (MG-Si).

Parameter		Raw material	Pellets	Product	Typical MG-Si
C (w%)	Min	0.8	0.1	<0.01	0.01
	Max	4.1	0.7	0.02	0.04
O (w%)	Min	2.4	3.0	-	
	Max	6.8	6.7	<0.1	<0.1
Fe (ppmw)	Min	2	9	151	2000
	Max	512	463	581 (1700)*	4000
P (ppmw)	Min	0.4	0.6	3.1	20
	Max	42	31	7.9	60

* Batches with Fe containing fragments

The P content is lower and more stable with respect to traditional MG-Si due to the general lower content in the main raw material – the KERF. Potential root cause for a slight increase between the different process steps is probably linked to mixing of different raw materials.
Other dopants, like B is not measured on sub-ppmw level in the campaign due to lack of instrumentation for this. However, a current detection limit of 1 ppmw is good enough for the intended use of the final product for MG-Si.

Fe increases with a factor of one order of magnitude from raw material to final product. Fe max increases due to melting of foreign fragments (Fig. 4), following the material stream, but not necessarily being reflected in the chemical analysis in the first part of the raw material handling. Elkem observe that these types of fragments come in waves, indicating that other waste streams occasionally are finding its way into the kerf material stream. Back-calculation from large scale testing at Elkem indicates that the recycled kerf can contain foreign fragments corresponding up to approximately 0.1–0.4 wt% Fe on a dry basis (per kg Si in the kerf as raw material). In addition to Fe, Ni was identified as an additional important metallic impurity in the kerf feedstock. Depending on wafering technology used, concentrations are found in the range from approximately 100 to 600 ppmw in the kerf. The variation in Ni seems to remain during the processing in pellet and melting plant.

3.3 Raw materials and their impact on the remelting process of slag

For the second recycling case, remelting of slags and sculls, control of the chemical composition of raw materials is critical for a successful process design. As the slags and sculls are considered a by-product of the silicon and ferrosilicon production processes, they are usually not analysed extensively. The silicon content in the slags and sculls is usually the only parameter that is analysed, but for remelting purposes a full chemical analysis is necessary.

Slags and sculls are in general inhomogeneous materials. They consist of areas with a lot of silicon and other areas with almost no silicon. In the areas with low silicon content, the slag chemistry may vary a lot in terms of which oxides and silicates are more prominent. Prior to a remelting process, crushing and mixing of the raw materials are thus important. Table IV gives an overview of the typical variations in slags and sculls after such processes for the most important chemical compounds in the large-scale testing carried out at Elkem Kristiansand.

Table IV: Typical variations for some chemical compounds in slags and sculls.

Material	Free silicon (wt. %)	SiO_2 (wt. %)	CaO (wt. %)
Slags	20-40	20-60	5-15
Sculls	25-50	20-70	2-10

3.4 Scale up: industrial campaign of remelting slag and skulls

The most important parameter used to measure product quality was free silicon content in the slag product for a cement or binder application. Elkem had set a target of less than 5 wt. % silicon left in the slag product for this purpose, where levels between 5–10 wt. % were considered acceptable. This parameter was thus monitored for the duration of the campaign, and the results are presented in Figure 7. As can be seen from the figure, the campaign showed a steady decline in free silicon content in the slag product, but achieving the target concentration below 5 wt. % was challenging. Several measures were implemented to optimise the separation of slag and molten FeSi, as reflected by the sudden dips in the figure, but the chemical equilibrium appeared to move towards higher silicon content in the slag product over time. The final measures, from batch 76 onwards, gave the best results. Changes to the practical furnace setup were the main contributor to this improvement. In addition, the operators had gained more experience in sorting slag products with high and low silicon content.

Figure 8: Free silicon content (wt. %) in slag product as a function of batch number.

An important basis for achieving a good separation of slag and silicon is the slag chemistry. A certain difference in density between the slag and silicon is necessary, and the slag must have a certain fluidity. Both properties are adjusted using CaO. Increasing the amount of CaO to the slag melt will increase the density and decrease the viscosity. A decrease in viscosity is positive for the fluidity of the slag melt, but an increase in density is negative in terms of density difference between slag and FeSi. This means the slag chemistry, or the CaO concentration, needed to be monitored closely during the campaign. For this, the term basicity was used, which is in operation mode defined as the ratio between CaO and SiO_2. Basicity measurements were obtained by performing chemical analyses on slag samples taken from the melt. However, this is a slow process which cannot sufficiently be used as a way of controlling the process during operation. Elkem has in the large-scale campaign investigated a new inline method for controlling the basicity of the slag.

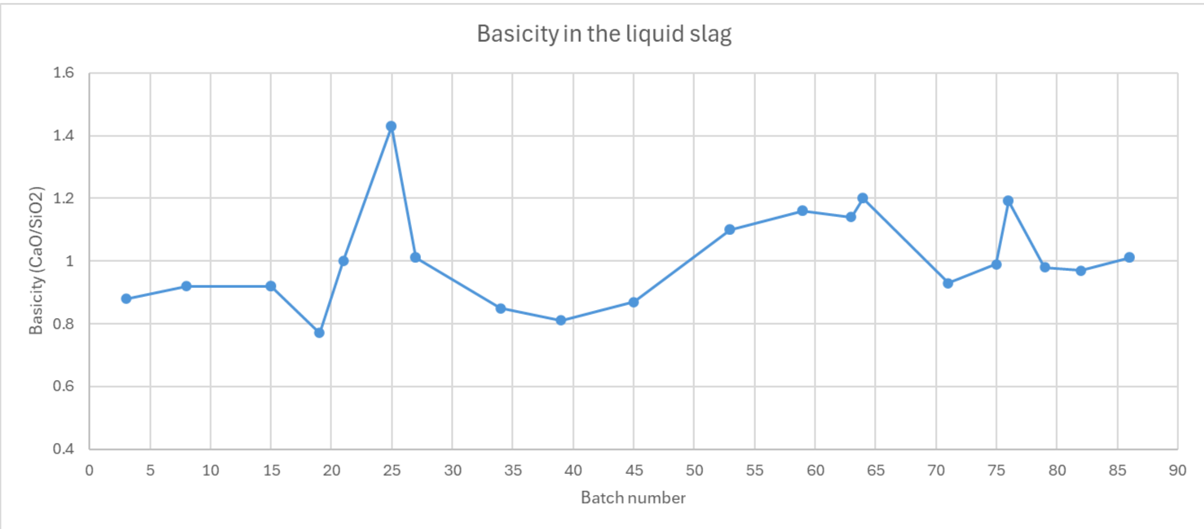

Figure 9: Basicity (CaO/SiO_2) of the liquid slag as a function of batch number.

The new measurement method, under development, generally give higher basicity for the slag than those obtained using chemical analyses. The method will be described on a later stage, when full validation is completed. In addition, it is observed that the inhomogeneity of the slag results in relatively large variation in basicity. Overall, the average chemistry of the slag was within acceptable areas in terms of density and viscosity. The results compared to small scale test might indicate that scale up and the setup of induction furnaces used for the large scale is the main reason for the challenges related to separation and product quality of slag. In smaller scale, separation of slag and FeSi have been performed successfully with slag products consisting of less than 5 wt. % free silicon (also commonly referred to as metallic silicon content). The root cause for the differences is currently not fully understood, but both design and setup of the systems are under investigation.

3.5 Pellet plant -Experiences and safety issues from the campaign

The pellet step was tested in two separate campaigns conducted in autumn 2025 and spring 2026. The campaigns verified the pellet plant as an industrial pilot and demonstration unit at Technology Readiness Level 7 (TRL7), and the produced material was internally qualified as within specification. At the same time, the campaigns demonstrated that variation in the raw materials is reflected in kerf reactivity during drying and calcination. This directly affects plant capacity, process stability and operational safety. These findings confirm that raw-material control is essential for reliable industrial recycling of silicon from kerf and indicate that tighter raw material specifications are required in future operation.

The campaigns further showed that the pellet line has a demanding process-safety profile, driven by combustible dust, reactive kerf behaviour, plugging in hot process zones, off-gas instability, and a control architecture that still reflects pilot-scale operation. The most critical scenarios are associated with dust fire or explosion, temperature escalation in the dryer and calciner, concealed overheating at blocked transfer points, and operator exposure during manual intervention and upset handling. The overall risk level is strongly influenced by dust containment, the robustness of automation and interlocks, uncertainty in off-gas oxygen measurement, burner-related hazards, and the need for a fully verified philosophy for atmosphere control, ventilation and emergency shutdown.

For further scale-up towards a TRL9 industrial design, the pellet plant should be assessed and developed as an integrated process-safety system. This requires updated HAZID (HAZard Identification) and HAZOP (HAZard and Operability) studies, combustible-dust assessment, hazardous-area classification, and a clearer basis for explosion prevention, atmosphere control strategy and shutdown logic. In parallel, operational robustness should be improved through tighter control of raw material with respect to reactivity, moisture and contamination. In addition, it is necessary to strengthen operating and corrective-action procedures, reduced need for manual intervention, improved housekeeping and maintenance, and systematic operator training. Collectively, these measures are required to close the gap between pilot-scale operation and a robust industrial operating window for kerf-based silicon recycling.

3.6 CO_2 Footprint Impact

Conventional submerged arc furnace (SAF) silicon production is dominated by Scope 1 emissions, with ~4.7–5.0 t CO_2 eq/t Si from carbothermic reduction using carbon reductants. Additional Scope 2 emissions arise from electricity consumption (~11–13 kWh/kg Si), while Scope 3 includes upstream mining of quartz and reductants, and transport of raw materials. For kerf-based recycling, the key shift is the potential of elimination of most Scope 1 emissions, as no primary reduction is required. The footprint is instead dominated by Scope 2 (electricity, low in Norway) and limited Scope 3 contributions (e.g. additives, logistics). Life-cycle studies indicate up to ~ 77% total emission reduction (Blömeke et al., 2023), implying that the main decarbonisation lever is elimination of most of Scope 1 emissions and that the product will remain with more manageable Scope 2 emissions, which can be reduced further via low-carbon electricity. This redistribution changes the relative contribution of raw material supply, process emissions and electricity consumption, and should therefore be considered when interpreting and comparing carbon footprint results.

In conventional cement production, Scope 1 emissions dominate, primarily from calcination of $CaCO_3$, contributing ~0.5–0.8 t CO_2 eq/t clinker. Scope 2 relates to kiln electricity, while Scope 3 includes raw material supply and downstream use. When slag is used as substitute for cement, most of the avoided emissions are Scope 1, as clinker production is displaced. The residual footprint of slag is largely Scope 2–3, linked to processing (e.g. grinding) and transport. Typical substitution yields ~0.7–0.8 t CO_2 eq savings per tonne of cement replaced. In practice, this shifts emissions away from hard-to-abate Scope 1 towards lower-intensity Scope 2–3 and enabling substantial net reduction in total embodied CO_2 eq in construction materials (He et al., 2022).

3.7 Further work

Future work will focus on expanding the experimental dataset and validating the process under more representative operating conditions. Particular emphasis will be placed on product consistency, silicon recovery, process stability, and environmental performance at increased scale. For silicon products targeting Si99 applications, such as the aluminium and chemical markets, future publications will include a broader characterization of the final product, including key impurity elements (e.g., Al, Ti, and Ca) and life-cycle assessment (LCA) results from regular operation. In addition, further process control needs to be implemented in order to handle the variation in element like Fe and Ni.

Further optimization studies are planned to improve process robustness and resource efficiency. However, several aspects of the technology remain under active development and contain some commercially sensitive know-how. Consequently, detailed information related to intermediate products, operating conditions, and proprietary process parameters is not disclosed at this stage. Such results may be reported in a more aggregated form as the technology matures and progresses towards industrial implementation.

4. CONCLUSION - SUMMARY

This paper presents two large-scale recycling cases at Elkem: recycling of silicon from kerf, and remelting of slags and sculls to produce a cement-replacement material with a lower CO_2 footprint.

Industrial scale testing on kerf recycling shows that silicon from wafer-sawing side streams can be upgraded to Si99 quality. A main finding is that variation in the incoming kerf, particularly in carbon, oxygen, moisture and foreign material, has a direct impact on process stability, safety and intermediate product quality. Among the monitored indicators, Fe has proven to be a practical and important KPI to follow up during processing, as elevated Fe levels reflect contamination from foreign metallic fragments that may enter and follow the process stream. At the same time, the results show that kerf-based recycling has a clear decarbonisation potential, since production can avoid most of the direct scope 1 CO_2 eq emissions associated with conventional carbothermic silicon production.

Production of slag suitable for replacement of cement by remelting of slag and skulls also demonstrates the importance of controlling the raw materials. The test campaigns show that the raw materials are inherently heterogeneous, with substantial variation in silicon content, SiO_2 and CaO, and that this variation must be managed through crushing, blending and close control of slag chemistry. The large-scale campaign confirmed the technical potential to recover FeSi and produce a slag for use as replacement for cement, but it also demonstrated that there are several challenges related to scale-up that remains to be solved, particularly with respect to stable operation of the process. Nevertheless, this case has a potentially significant CO_2 benefit because the slag product can replace part of the clinker in cement applications and thereby reduce the direct process emissions associated with conventional clinker production

While the results confirm the technical feasibility of the proposed recycling routes, further work is ongoing to establish more detailed product qualification data and environmental performance metrics required for commercial implementation in some selected Si99 markets.

5. ACKNOWLEDGEMENTS

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