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Recycling Silicon Kerf Waste and Quartz Pot Scrap for Silicon Production Via Carbothermic Reduction

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Abstract. The rise in photovoltaic (PV) waste across all stages of the PV value chain has created a need for efficient recycling solutions to reintroduce these materials into use. In response, the EU project (ICARUS) is exploring several recycling routes for key waste streams, including silicon kerf, quartz (used crucibles and pot scrap), and graphite (furnace insulation), for silicon production. This paper presents the development of a carbothermic recycling route that uses waste crucibles, pot scrap, and kerf as raw materials for silicon production. Silicon was produced in a pilot-scale submerged arc furnace, and its purity was analyzed using ICP-MS to quantify trace impurities and overall purity. The results showed that the silicon that is produced from waste materials closely matches the characteristics of metallurgical-grade silicon. These findings demonstrate the technical feasibility of waste materials in silicon production, with significant implications for industrial practices, sustainability efforts, and future policies aimed at promoting circular economies in high-demand sectors like silicon production.

Keywords: Silicon Kerf Waste, Crucible Scrap, Recycling, Carbothermic Reduction, PV Silicon

1. Introduction

As photovoltaic (PV) installations continue to grow, the resulting waste streams from PV value chain are also increasing. Silicon kerf, graphite, and silica wastes from this industry are largely landfilled as inert materials, with only a small portion being reused. This leads to low re-source use efficiency and a significant environmental impact, requiring urgent need for more effective recycling practices in silicon production. Silicon kerf and crucible/pot scrap represent significant portions of the PV industry waste, and their quantities are expected to rise as demand for silicon continues to increase, making their recycling important. According to projections based on studies [1] and [2], the estimated global silicon kerf waste generation from PV manufacturing process in 2023 is approximately 387 kMT (kilo metric tons). This includes contributions from wire sawing, as well as kerf generated during cropping, squaring, chamfering, and grinding processes.

Similarly, the global crucible and pot scrap waste is estimated at 88.8 kMT and 9.88 kMT, respectively for the same year.

In general, various studies in the literature have primarily focused on refining the large volumes of silicon kerf generated during different stages of silicon wafer production [3] and re-cycling these materials through melting [4]. Less attention has been given to alternative recycling techniques such as carbothermic reduction. This paper addresses this research gap by exploring the technical feasibility of using waste silicon kerf waste and crucible scrap as raw materials for silicon production in carbothermic reduction processes in a submerged arc furnace (SAF). The study aims to evaluate the potential of these waste materials to produce high-purity silicon and assess their suitability for industrial-scale applications, contributing to both resource efficiency and sustainability in silicon production for PV and other applications.

The remainder of this paper is organized as follows. Section 2 describes the materials and methods, including the research context, characterization of waste materials, preparation of self-reducing briquettes through briquetting, and operation of the submerged arc furnace (SAF). Section 3 presents the results of silicon production using the SAF, detailing both the quantity of silicon produced and its purity analysis. Finally, Section 4 provides concluding remarks along with recommendations for future research.

2. Materials and Methods

This section provides a brief overview of the research, describes the waste materials and their characterization for silicon production, and details the charge preparation and experimental setup.

2.1 Research Context

The research presented in this paper is part of the ICARUS project, funded under the Euro-pean Union's Horizon 2020 research and innovation programme [5]. The ICARUS project aims to demonstrate modular processing solutions at an industrial scale, targeting the recovery of up to 95% of high-value raw materials generated during silicon ingot and wafer manufacturing. Specifically, this work belongs to a work package which aimed to reintroduce silicon kerf, graphite, and silica waste back into the silicon value chain through carbothermic reduction. It is part of four experimental campaigns conducted in a pilot-scale SAF.

The work conducted in this paper can be summarized as shown in Figure 1. It primarily consists of four stages. The first stage involves the collection and pretreatment of raw materials, including silicon kerf and silicon pot scrap. It includes processes such as washing, drying, grinding and characterization of the materials. The second stage is agglomeration, in which these pretreated raw materials are briquetted into self-reducing briquettes with optimal stoichiometry for carbothermic reduction. The third stage consists of semi-pilot-scale carbothermic reduction experiments to produce silicon in a SAF. Finally, various tests are conducted to analyse the purity of the produced silicon.

2.2 Characterization of Waste Materials

The waste materials used in this study were characterized using LECO (Combustion Analysers) and ICP-MS (Inductively Coupled Plasma Mass Spectrometry) analysis for

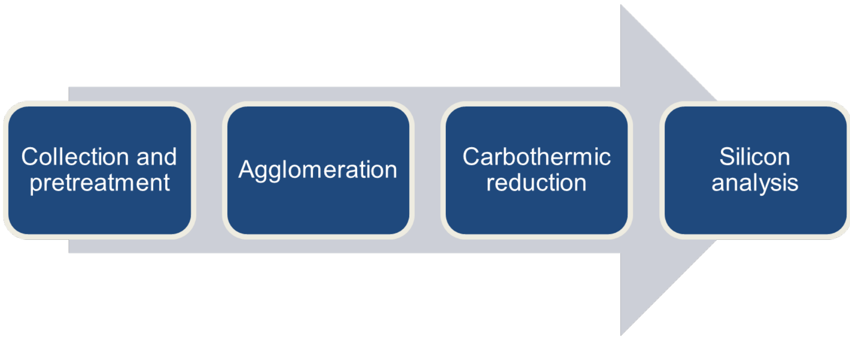

Figure 1. *Carbothermic reduction of waste materials for silicon production.*

the kerf, and XRD (X-ray Diffraction) for the pot scrap. LECO analysis of the kerf samples showed an average carbon content of 1.21 wt.% with a standard deviation of 0.08, and an oxygen content of 4.44 wt.% with a standard deviation of 0.05. Similarly, ICP-MS analysis was performed to measure the impurity content in the silicon kerf samples. The results indicate that the main dopant impurities are phosphorus (P) and gallium (Ga), while calcium (Ca) is the metallic contaminant with the highest concentration. On the other hand, the pot scrap used in this study has an average particle size of less than 200 μm. It primarily contains SiO_2 from the crucible, along with some silicon. XRD analysis was performed to determine the precise levels of Si and SiO_2 in a sample of powdered pot scrap. The analysis showed three main phases in the sample: Si (16%), SiO_2 cristobalite (2%), and amorphous SiO_2 (82%).

2.3 Agglomeration of Charging Material (Briquetting Process)

Briquetting is used as an agglomeration method to reintroduce the waste materials for carbothermic reduction in a SAF. For this purpose, quartz source materials, such as pure quartz, silicon kerf and pot scrap, and carbon source material, such as pure carbon black, are used. These materials are agglomerated into self-reducing briquettes using briquetting machine. Three types of briquettes were made for the experiment: Type I (pure quartz and carbon black with binder and water), Type II (pot scrap, carbon black, binder, and water), and Type III (silicon kerf with binder and water). The briquettes were produced using a DMSMAC briquetting machine, Figure 2. The green briquettes were heat-treated to ensure that they possess sufficient mechanical strength and low moisture content, enabling them to withstand the rigors of charging into the SAF. This heat treatment included both drying in a heating cabinet at 105 $^{\circ}C$ for 12–24 hours and burning at 200 $^{\circ}C$ for another 12–24 hours.

Figure 2. *Briquetting process. DMSMAC briquetting machine and sample briquettes.*

2.4 Submerged Arc Furnace Operation

Silicon is primarily produced through carbothermic reduction in a submerged arc furnace. The process involves mixing quartz with a carbon-containing material and then heating the mixture to high temperatures. During this process, carbon reduces silicon dioxide to produce molten silicon, which is subsequently cooled and solidified into silicon blocks. For this work, an in-house-built pilot-scale SAF furnace was used to conduct two experimental campaigns (on separate days, one year apart). Each campaign consisted of two pilot experiments, totaling four experiments. These are:

- Pilot 1: Type I briquettes and quartz lumps as charge.
- Pilot 2: Type I briquettes, quartz lumps, and pot scrap lumps as charge.
- Pilot 3: Type II briquettes and pot scrap lumps as charge.
- Pilot 4: Type II & III briquettes and pot scrap lumps as charge.

The experiments aim to investigate the use of self-reducing briquettes made from waste materials in SAF furnace for silicon production. The experimental campaigns were run over a period of three days and three nights. These experimental campaigns included several key activities including preheating the furnace, operating the furnace, preparing the charge mate-rial, conducting rodding and tapping operations. Figure 3 shows some of the activities in these campaigns.

Figure 3. *Main submerged arc furnace operations in the campaign.*

In SAF operation, electrical power is supplied through carbon electrodes submerged directly into the charge material. Electric current passes through the charge, generating intense heat due to resistance, leading to extremely high temperatures within the furnace that drive the carbothermic reduction reaction. In normal operation, the experiments were run in current control mode, and the process operator varies the current around 3 kA to achieve a 140–160 kW load. The voltage is measured and controlled by current, the electrode position, and burden resistance.

3. Result and Discussion

This section presents the results from two experimental campaigns, comprising a total of four pilot experiments. The objective of these campaigns was to produce metallurgical-grade silicon using self-reducing briquettes made from pure and waste materials, specifically silicon kerf and silicon pot scrap through carbothermic reduction in SAF.

3.1 Campaign 1 (Pilots 1 and 2)

In this SAF campaign, conducted in June 2023, approximately 60 kg of silicon was produced across six separate tapping operations during the two pilot experiments. Silicon was produced using self-reducing briquettes made from both virgin and waste materials. Additionally, pure quartz lumps were used in Pilot 1, and pot scrap lumps were used in Pilot 2 as additional charge materials. The purity of the produced silicon was assessed by analysing six samples from each tapping operation using ICP-MS analysis, which quantifies trace impurities to determine the overall purity of the sample. Table 1 summarizes the results of this analysis. From this table, it can be concluded that the produced silicon meets the purity requirements for metallurgical-grade silicon [6]. Additionally, the purity is consistent across the various samples.

Table 1. *Purity of the tapped silicon measured by ICP-MS in campaign 1 in both pilots.*

Sample	1	2	3	4	5	6
Pilot 1 & 2 (%)	97.89	98.27	98.47	98.39	98.34	98.79

Detailed results from the ICP-MS analysis, quantifying trace impurities concentration levels, are illustrated in Figure 4 for dopants and Figure 5 for metallic impurities. The results show the presence of dopant impurities such as boron (B), phosphorus (P), and gallium (Ga). Phosphorus was found to be the most prevalent dopant and that its concentration level in all the tapping is slightly above the threshold for metallurgical grade silicon [6]. The concentrations of both B and Ga are well within the threshold for metallurgical grade silicon. Similarly, the ICP-MS analysis also showed the presence of metallic impurities such as aluminium (Al), iron (Fe), calcium (Ca), titanium (Ti), chromium (Cr), nickel (Ni), copper (Cu), and manganese (Mn) in the sample silicon (Figure 5). The concentration of Al exceeds the threshold for metallurgical grade silicon in the first four tapping but falls within the limits in the last two tap-ping. For Fe, only the first, third, and last tapping having concentrations within the limit. Calcium exceeds the threshold only in the first tapping. In contrast, Ti impurity concentrations are above the threshold across all tapping. The impurity concentrations of Cr, Ni, and Cu are all within acceptable limits. Despite the above variations, it can be concluded that the concentrations of most impurities are generally within acceptable limits for metallurgical grade silicon, showing the material's suitability for further applications [6].

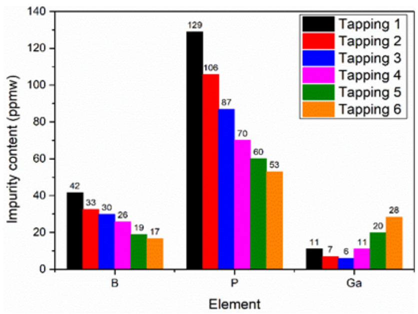

Figure 4. *Dopant impurities in the tapped silicon samples in campaign 1.*

3.2 Campaign 2 (Pilots 3 and 4)

In this SAF campaign, conducted in May 2024, approximately 32 kg of silicon was produced across six separate tapping operations. Unfortunately, only Pilot 4 produced

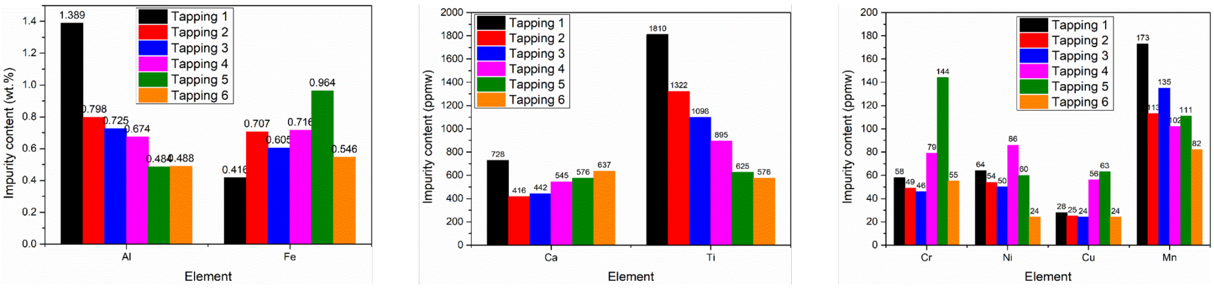

Figure 5. *Metallic impurities in the tapped silicon samples in Campaign 1.*

silicon during this campaign. The reason why Pilot 3 did not produce silicon remains unclear, and further analysis is required to identify the underlying cause. Silicon was produced using self-reducing Type II and Type III briquettes, along with pot scrap lumps as charge materials. Like the previous campaign, the purity of the silicon produced was assessed using ICP-MS analysis of six samples from each tapping operation. Table 2 summarizes the results of this analysis, indicating that the produced silicon meets the purity requirements for metallurgical-grade silicon [6] and has slightly higher purity compared to silicon from the previous campaign.

Table 2. *Purity of the tapped silicon measured by ICP-MS in campaign 2 pilot 4.*

Sample	1	2	3	4	5	6
Pilot 4 (%)	98.43	98.16	98.01	98.39	98.47	99.05

Similar to the previous campaign, detailed ICP-MS analysis results, quantifying trace impurity concentrations, are presented in Figure 6 for dopants and Figure 7 for metallic impurities. The results indicate the presence of dopant impurities such as boron (B), phosphorus (P), and gallium (Ga). Phosphorus (P) was again found to be the most prevalent dopant, alt-hough its concentration was significantly lower compared to the previous campaign. However, P levels remain slightly above the threshold for metallurgical-grade silicon. Similarly, boron concentrations were significantly lower and within the acceptable threshold. In contrast, higher concentrations of gallium impurities were detected.

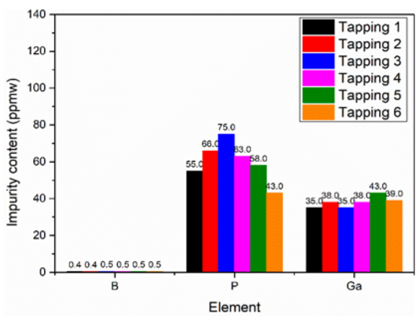

Figure 6. *Dopant impurities in the tapped silicon samples in Pilot 4.*

The metallic impurities detected include aluminium (Al), iron (Fe), calcium (Ca), titanium (Ti), chromium (Cr), nickel (Ni), copper (Cu), and manganese (Mn) (Figure 7). The concentration of Al in these samples is significantly lower than in the samples from the previous campaign. The first four tapping have Al concentrations that are slightly above the threshold for metallurgical grade silicon, while the last two tapping have Al concentrations well within the threshold limit. For Fe, all tapping have concentrations within the acceptable limit. However, the Ca and Ti impurity concentrations are higher in these samples compared to the previous campaign and are well above the threshold. Similarly, the Cr and Ni impurity contents are high and exceed the threshold limits for metallurgical grade silicon. On the other hand, the concentrations of Cu and Mn are well within the acceptable limits. All in all, the silicon produced in this campaign has a purity and characteristics comparable to metallurgical grade silicon [6]. This is a significant finding because 70% of the materials used in this campaign came from waste pot scrap and waste silicon kerf, unlike the previous campaign.

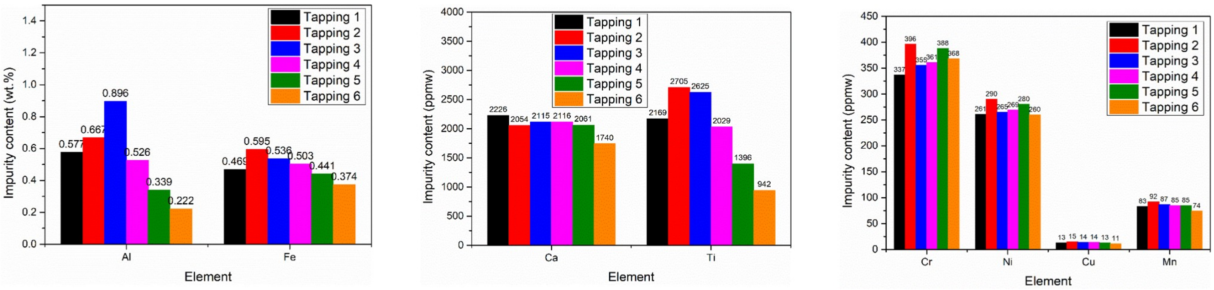

Figure 7. *Metallic impurities in the tapped silicon samples in Pilot 4.*

4. Conclusion

This study presented the work conducted in the two experimental campaigns comprising four pilot-scale experiments which aimed at producing metallurgical-grade silicon using self-reducing briquettes made from both pure and waste materials (silicon kerf and pot scrap) through carbothermic reduction in a submerged arc furnace. Overall, these results highlight the technical feasibility of using self-reducing briquettes from waste materials for producing metallurgical-grade silicon, thereby supporting sustainable practices within silicon manufacturing. The silicon purity that is achieved using waste materials has significant implications for reducing the environmental footprint and cost of silicon production. Additionally, the use of waste silicon sources such as kerf and pot scrap offer a promising pathway for resource recovery and waste minimization. Future work should focus on further optimizing recycling processes, particularly addressing dopant impurities and metallic contaminants. Additional efforts should also address operational challenges, such as the production inconsistencies observed between pilot experiments. Furthermore, the demonstrated technical feasibility should be complemented by comprehensive assessments of economic viability and environmental impacts. Only this holistic approach will pave the way for more sustainable and cost-effective silicon production practices.

Data availability statement

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

Author contributions

Birgit Ryningen: Conceptualization, Formal analysis, Methodology, Supervision, Writing – original draft, and Writing – review & editing; Berhane Darsene Dimd: Conceptualization, Formal analysis, Methodology, Data curation, Visualization, Writing – original draft, and Writing – review & editing; Nagarajan Somi Ganesan: Formal analysis and Writing – original draft; Pål Tetlie: Methodology and Writing – original draft; Irene Bragstad:

Methodology and Data curation; Martin Bellmann: Conceptualization, Methodology, Supervision, and Writing – review & editing; Roar Jensen: Conceptualization, Methodology, and Supervision; Arvid Inge Sørvik: Methodology and Supervision; Torfinn Krogstad: Methodology and Supervision.

Competing interests

The authors declare that they have no competing interests.

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References

[1] P. Brailovsky et al., "Insights into circular material and waste flows from c-si pv industry", *EPJ Photovoltaics*, vol. 14, p. 5, 2023. DOI: 10.1051/epjpv/2022029.

[2] "Pv manufacturing in europe: Understanding the value chain for a successful industrial policy", ETIP PV Industry Working Group White Paper, European Technology and Innovation Platform for Photovoltaics, Tech. Rep., 2023.

[3] H. Yang, I. Liu, C. Liu, H. Hsu, and C. Lan, "Recycling and reuse of kerf-loss silicon from diamond wire sawing for photovoltaic industry", *Waste Management*, vol. 84, pp. 204–210, 2019. DOI: 10.1016/j.wasman.2018.11.045.

[4] J. Kong et al., "An economical approach for the recycling of high-purity silicon from diamond-wire saw kerf slurry waste", *Silicon*, vol. 11, no. 1, pp. 367–376, 2019. DOI: 10.1007/s12633-018-9889-x.

[5] ICARUS H2020 Project. "Processing and refining of secondary raw materials from silicon photovoltaic manufacturing", Accessed: Aug. 12, 2025. [Online]. Available: https://www.icarus.eu.com/.

[6] WikiChip. "Metallurgical-grade silicon (mgs)", Accessed: Aug. 12, 2025. [Online]. Available: https://en.wikichip.org/wiki/metallurgical-grade_silicon#google_vignette.