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Transition to Carbon Neutral Silicon Production at Wacker Holla

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Abstract – This paper describes ongoing work carried out at Wacker Chemicals Norway AS, Holla Metall, to make the silicon plant carbon neutral by 2030 through large-scale substitution of fossil reductants with biocarbon. The transition requires changes to logistics, especially related to handling and use of low-density and mechanically weak materials that generate fines and dust. Full-scale industrial test campaigns have been conducted with biocarbon shares exceeding 50% of the total carbon demand, demonstrating that stable furnace operation is possible. During testing, temporary fluctuations in silicon yield are observed, mainly associated with ramp-up phases, variability in fines generation, and controlling the effective carbon input. The work highlights differences between charcoal and agglomerated biocarbon materials in terms of reactivity, mechanical stability, and operational behavior, and highlights the need for improved control of material properties and operating strategies. A structured qualification methodology combining laboratory testing and industrial validation has been developed to support implementation. The results show that successful use of biocarbon requires looking at the full process. Major research and development projects are carried out in-house as well as in collaboration with universities, research companies and other industry including both established and new producers of biocarbon materials.

1. Introduction

In recent years, the importance of biocarbon has grown. Driven by carbon neutrality targets and supported by the development of agglomerated products, significantly higher substitution levels have become technically feasible. Industrial experience from Brazil and other parts of South America shows that silicon production with mainly biogenic reductants is possible when the process is designed accordingly (Minasligas, 2026; LIASA, 2026). However, these operations face similar challenges related to variability in charcoal quality, which affects carbon utilization (Isbaex, 2014).

In a previous publication, Wacker Chemicals Norway AS, Holla Metall, hereafter referred to as Wacker Holla, presented its strategy towards carbon neutral silicon production, emphasizing the role of biocarbon substitution and outlining key technical challenges associated with this transition (Halland, 2024). Particular attention was given to the variability in mechanical and thermal strength, fines and dust generation, which highlighted the need for industrial validation to fully understand the implications of this transition. The overall objective of significantly reducing greenhouse gas emissions remains unchanged. Wacker Holla continues to target carbon neutral silicon production by 2030 through large-scale substitution of fossil reductants with sustainable biocarbon materials, combined with adaptation of raw material systems and furnace operation.

This article builds on the consideration already set out and presents operational experience from multiple industrial test campaigns. While the previous study focused on feasibility and strategy, the present work documents the behavior of biocarbon under full-scale furnace

conditions. The analysis is based on campaigns starting in 2020 and subsequent tests with increasing operational experience. Attention is given to the differences between charcoal and agglomerated biocarbon, and their impact on furnace behavior, process stability, and material handling. The evolution of operating strategy is also described, reflecting the transition from exploratory testing to more controlled implementation.

2. Role of Biocarbon in Silicon Furnace Operation

In the carbothermic silicon process, carbon (C) acts as the reducing agent for silica and participates in reactions involving silicon monoxide (SiO) gas, including the formation of silicon carbide (SiC) and subsequent silicon production. The ability to capture SiO gas directly influences silicon yield and energy efficiency. In addition, carbon affects gas generation, burden permeability, and electrical resistance, making its properties critical for stable furnace operation.

A key reaction is the capture of ascending SiO gas through SiC formation, shown in following reaction:

$$SiO_{(g)} + 2C_{(s)} = SiC_{(s)} + CO_{(g)} \quad [1]$$

The efficiency of this reaction depends on the availability and reactivity of carbon surfaces, as well as the distribution of carbon in the charge. In this respect, biocarbon behaves quite differently from conventional fossil carbon materials. In general, its higher porosity and reactivity can improve the reaction rates, but at the same time it can become less stable, as it tends to break down and form finer fractions. Because of this, biocarbon needs to be considered not only as a chemical reactant, but also as part of the furnace structure, influencing permeability, gas flow, and electrical behavior.

3. Qualification Methodology for Biocarbon Materials

Due to the variability and complex behavior of biocarbon materials, a structured qualification methodology is required prior to industrial use. Experience has shown that neither appropriate material properties nor furnace behavior can be predicted from a single dataset. An iterative approach combining supplier data, laboratory testing, and industrial validation is therefore applied. Evaluation is carried out stepwise, starting with simple and low-cost assessments, and progressing to more detailed testing only for materials that demonstrate acceptable performance. This approach minimizes the use of resources on unsuitable materials.

The process begins with a review of supplier-provided data, including chemical composition, ash chemistry, and basic physical properties. In parallel, supplier capability, scalability, logistics, and compliance with sustainability requirements are evaluated. Materials that pass this stage are tested by an in-house laboratory, using small sample quantities. This includes verification of full chemical analysis, thermal behavior, and resistance to degradation during handling. Mechanical stability is first assessed through a drop test, designed to simulate the maximum drops encountered in the raw material handling system. In addition, a simple but informative crushing test is performed, where the material is deliberately broken using momentum transfer and localized pressure to provide a qualitative, comparative assessment of its mechanical strength and how it breaks up. Moisture behavior is also evaluated, both in terms of uptake and resistance. Thermal resistance is evaluated by heating the material to approximately 1000 °C for 10 minutes in an inert atmosphere, providing an indication of its stability during the early stages of furnace exposure.

Further testing is conducted externally, including SiO reactivity and mechanical strength by tumble testing. Materials that pass these stages are considered for pilot-scale tests. Such tests are intended to expose the material under more representative conditions. However, while these evaluations provide valuable information, they are not sufficient to fully predict industrial behavior. As a result, controlled full-scale trials remain a necessary step in the qualification process, representing the final validation before potential implementation.

Industrial testing is performed by gradually introducing the material into our dedicated test furnace of about 17 MW. For new products we will use enough material for a trial lasting about a month on 30% of the total carbon demand, ramping up from 20% as the starting point.
If we consider the industrial test a success, we will either start testing on higher shares, exceeding 50% of the total carbon demand, or use one of the larger furnaces which has semi-continuous filling through charging tubes instead of the batchwise filling by truck on the smaller test furnace. The larger furnaces also have higher accumulation of drop length throughout the raw material handling system, increasing the risk of fines and dust generation.

Wacker Holla has already run several full industrial scale tests for biocarbon materials. During these campaigns, key performance indicators such as furnace stability, dust formation, silicon yield, and electrical response are closely monitored. Only materials that demonstrate stable and predictable behavior under these conditions are approved for long-term use. This structured process has proven essential for managing the risks associated with introducing new biocarbon materials.

In 2025 Wacker reached a new milestone: a long-term contract with a US-based producer of biogenic carbon and biohydrogen products. The contract came into force following a successful completion of the full qualification process. The biogenic carbon is to be produced in a new manufacturing plant built in the USA. The agreed volumes will cover a substantial portion of Wacker Holla's total carbon demand, marking a major step towards climate neutral silicon production.

4. Industrial test development and learning progression

Historically, the use of small amounts of charcoal and wood chips in the carbon mix has been common industry practice. Charcoal has typically served as a supplementary carbon source, mainly due to its relatively low impurity levels and high porosity. For most producers its use has nevertheless been limited, as large-scale substitution has been restricted by low density, high fines/dust generation, and challenges related to stability, supply and cost. This is also the case for Wacker Holla.

4.1 Operational and HSE challenges

At Wacker Holla, initial industrial campaigns were carried out to test high levels of biocarbon substitution under conditions largely based on conventional operation. Operation could be maintained at moderate substitution levels, confirming that biocarbon can function as a reductant. At the same time, several challenges were identified, including increased gas generation, variability in furnace stability, reduced yield, and changes in by-product composition.

In this work, particle fractions are differentiated based on their impact on handling and furnace operation. *Dust* refers to particles on the micrometer scale, which are prone to becoming airborne during handling and transport, representing the main Health, Safety and Environment (HSE) concern. *Fines* refer to particles that may leave the furnace with the off gas,

depending also on particle density and gas flow conditions, or that may accumulate within the burden and disrupt gas flow and permeability.

Significant HSE challenges were also observed. Dust formation occurred throughout the material handling chain, including unloading, storage, transport, weighing, and charging. This led to accumulation of dust in several areas, increasing the risk of self-heating and ignition, as well as explosion. Dust was also found to accumulate in critical equipment, such as feeding systems, leading to failures and unplanned stoppages. Mitigation measures were implemented to address these issues. Dust suppression systems were introduced, cleaning routines intensified, and monitoring of material temperatures in storage and silos was improved.

One of the most important process-related observations was the extent of variability in raw material behavior. Fluctuations in moisture content and fines distribution were much greater than typically observed for fossil carbon materials. This introduces a significant unknown variation in the carbon loss and complicates process control. The fines that are not blown off with the process gas can end up altering the permeability of the burden and hindering uniform gas flow. Uneven gas distribution reduces the effective SiO-reactivity of the charge, which is unwanted. The extent of these fluctuations is shown in Figures 1 and 2.

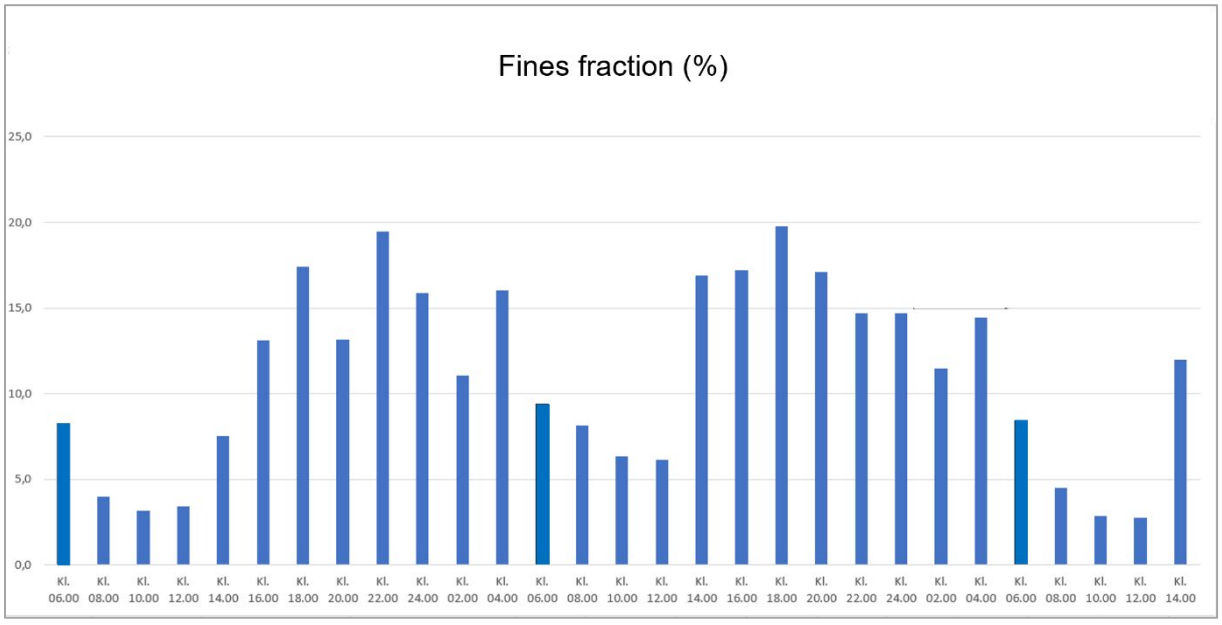

Figure 1: Fines fraction (%) for charcoal in the weighing cell as a function of time.

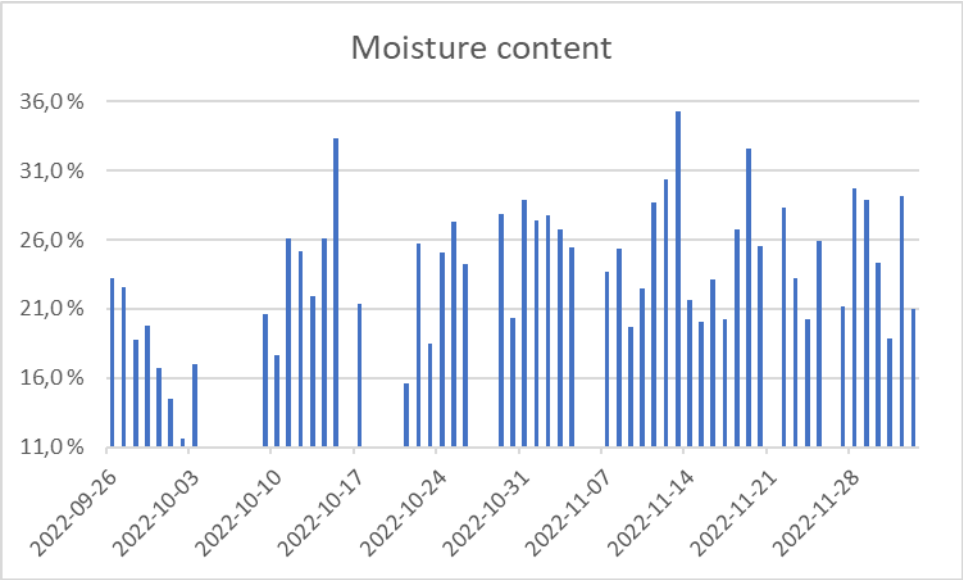

Figure 2: Moisture content (%) of charcoal as a function of time.

A distinct daily variation in fines fraction was observed, linked to filling of the day bins. This indicates that segregation during storage and handling was a major source of variability in the weighed charge mix. Part of the observed instability was also related to operating practice. Furnace parameters were adjusted frequently in response to uncertainty in material behavior. The resistance set point was often changed based on assumed differences in electrical properties, and the carbon balance was repeatedly adjusted to compensate for assumed daily variations in blow-off and burn-off. Frequent changes reduced process stability and made it difficult to identify the underlying causes of instability. Operation became reactive, with adjustments made to short-term fluctuations rather than allowing the furnace to stabilize.

It became clear that stable furnace operation required more consistent input materials. Stable moisture content, controlled particle size distribution with low fines content and predictable carbon input are all necessary to maintain predictable furnace conditions. Later campaigns were conducted with improved control of both materials and operation. Methods reducing segregation significantly were developed and implemented. Adjustments were made more conservatively and typically one at a time, allowing the response of the furnace to be observed before further changes were introduced. This marked a transition from reactive to controlled operation.

Additional improvements were made to charge composition, layering, and material flow through the furnace. Greater control of residence time and charge burden structure contributed to more stable reaction conditions. These changes resulted in a clear improvement in furnace stability, even at substitution levels above 50% of the carbon demand. The results show that many of the challenges observed in early campaigns were not only inherent to biocarbon but also related to operating strategy.

4.2 Impact on silicon yield and carbon balance

The sensitivity of silicon yield to carbon balance makes accurate control particularly important during biocarbon testing. From our experience, for a well-operated silicon furnace, a 1%

reduction in effective carbon balance typically corresponds to approximately a 2% reduction in silicon yield. Variations in fines generation and carbon losses can therefore have a significant impact on furnace performance and complicate interpretation of test results. The development of silicon yield during a full-scale campaign on our designated test furnace, using agglomerated biocarbon, is shown in Figure 3.

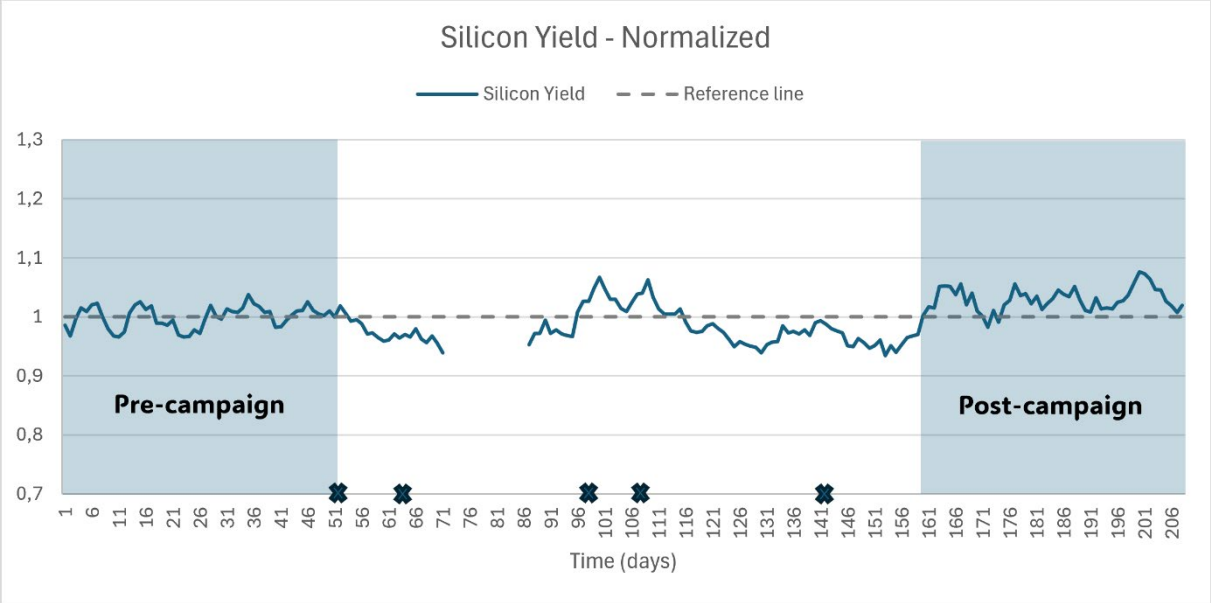

Figure 3: Normalized silicon yield relative to the average value of the 50-day pre-campaign period. Shaded regions indicate pre- and post-campaign operation. Crosses mark the ramp-up steps. The curve is a five-day symmetrical average. Days with furnace load less than 90% are removed from the data set. The break in the curve is a yearly maintenance stop including the following ramp up period. The stepwise increases in biocarbon share are shown with "X".

The results show that, although temporary fluctuations and short-term reductions in silicon yield occur during the campaign period, the average yield remains close to the reference level. The initial drop in silicon yield in the 95-day long biocarbon test indicates the learning curve for adjustments of electrical setpoints and carbon content at the start. The observed decreases in silicon yield coincide, with one exception discussed below, with the stepwise increases in biocarbon substitution. Following each increase, the process is stabilized on an acceptable yield before further ramp-up steps are introduced. This sometimes takes more time than in the original test plan, but the curve shows the empirical learning process done after every biocarbon increase.

The behavior observed in Figure 3 must be interpreted in the context of the time required to evaluate process performance when introducing new biocarbon materials. Several months of stable operation are needed to determine the actual impact on carbon losses and corresponding silicon yield, particularly for materials that generate significant amounts of fines. Variations in fines content influence the effective carbon input and may only become evident over extended periods. Similarly, determination of optimum electrical operating conditions requires time, since changes in raw material properties affect burden resistivity and furnace response. Temporary reductions in silicon yield of approximately 2–3% should therefore be expected during industrial qualification campaigns and are not necessarily an indication of poor material performance. Similar behavior is frequently observed during testing of new fossil carbon materials, where both furnace operation and carbon balance require optimization before representative performance can be established.

The post-campaign period shows a clear increase in normalized silicon yield relative to both the campaign and reference periods, providing additional insight into the overall carbon balance of the process. This behavior is consistent with a temporary excess of carbon during the biocarbon campaign, resulting in accumulation of (SiC) in the furnace. The subsequent increase in yield corresponds to operation at lower fixed carbon input, where this accumulated SiC is gradually consumed, leading to improved silicon recovery. Similar behavior is observed during the campaign period between approximately day 95 and 115, where an increase in silicon yield coincides with reduced fixed carbon input following a period of higher carbon addition. This boosts the silicon yield temporarily and delays the expected decrease in yield from the ramp ups on day 98 and day 107.

A contributing factor to this behavior may be overestimation of carbon losses associated with increased fines generation, resulting in operation with a higher effective carbon input than intended. These effects tend to be particularly pronounced with increasing biocarbon shares, as both fines generation and changes in burden resistance are amplified.

Another factor influencing furnace performance is the volumetric nature of biocarbon materials. Because biocarbon generally contains less fixed carbon per unit volume than fossil reductants, larger material volumes must be charged to maintain the desired carbon balance. This may reduce the residence time of other carbon materials in the furnace. As a consequence, fossil reductants may participate less effectively in SiO capture reactions and subsequent SiC formation, reducing their effective reactivity. The influence of this mechanism is expected to diminish at very high biocarbon substitution levels because the remaining fraction of fossil carbon becomes progressively smaller.

Overall, the results indicate that the process was not fully optimized during the campaign period. Nevertheless, stable operation was maintained at biocarbon substitution levels exceeding 50% of the total carbon demand, while the average silicon yield remained close to the reference level. The remaining yield differences are believed to be largely related to carbon balance control, electrical optimization, and operational adaptation, rather than to fundamental limitations of the biocarbon materials themselves.

4.3 Charcoal versus agglomerated biocarbon

The industrial campaigns highlighted significant differences between charcoal and agglomerated biocarbon products. Although both material types can function as reductants in silicon production, their properties differ considerably. Charcoal represents the simpler form of biocarbon and is characterized by a highly porous structure and high reactivity towards SiO. Industrial experience shows that charcoal-rich charges often promote uniform gas distribution and material flow, both of which increase the silicon yield.

However, the same porous structure that gives charcoal its high reactivity also results in lower mechanical strength. Material degradation during transport, handling, and charging therefore remains a significant challenge. The resulting particle-size variability complicates process control and can make furnace behavior less predictable. Industrial implementation of high charcoal shares therefore requires careful control of raw material quality and handling conditions.

Agglomerated biocarbon products, including briquettes and extruded materials, are produced through densification of finer carbon fractions, typically with the addition of binders. The principal advantage of these materials is improved mechanical robustness. Densification reduces particle degradation, improves particle-size consistency, and enables more

predictable feeding behavior throughout the raw material handling system. From an operational perspective, these properties contribute to greater process stability.

The improved mechanical durability of agglomerated products is reflected both in laboratory testing and industrial operation. Figure 4 compares tumble-test performance and fines generation measured during plant trials. Materials with higher tumble-test retention generally produced less fines during industrial use.

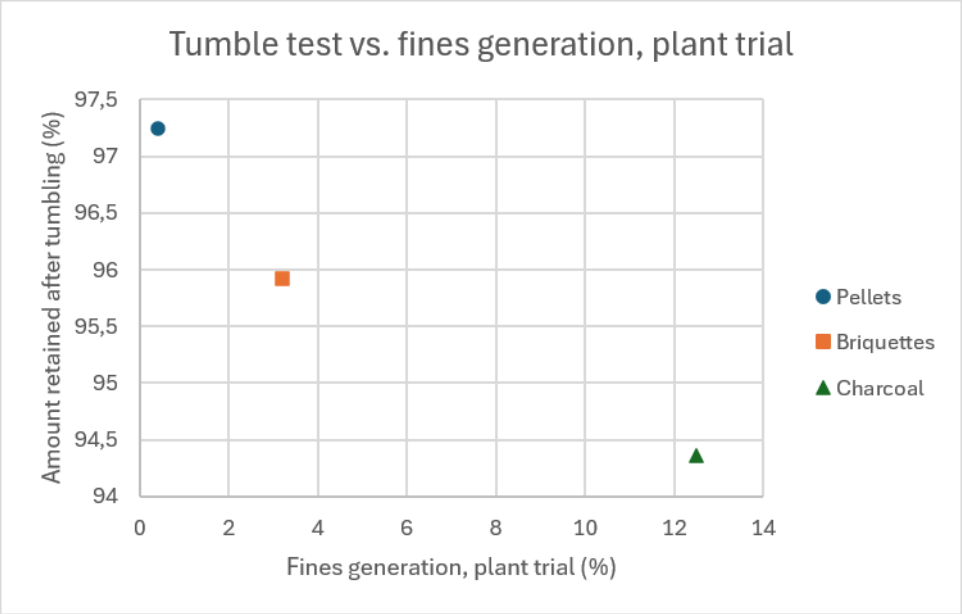

Figure 4: Relationship between tumble-test retention and fines generation during industrial trials. Tumbling results are based on the average of several pellets, briquettes and charcoal types.

The results show clear reduction in fines generation for the agglomerated products compared with charcoal. However, during industrial testing it was observed that dust formation during handling of briquettes was similar to amounts observed during handling of charcoal. While agglomeration can reduce the formation of larger fine fractions and improve process control, the generation of airborne particles may still remain sufficiently high to require dedicated dust mitigation measures.

Thermal stability is another consideration. While agglomerated materials are mechanically robust, partial disintegration during heating has been observed, indicating that their behavior under furnace conditions is strongly dependent on the type and performance of the binder system used. The moisture resistance of agglomerated materials is strongly dependent on both the type of binder system and the agglomeration method; while some combinations provide improved resistance to water uptake, others may promote moisture absorption and lead to deterioration during storage and handling. The selection of binder is therefore critical, as it directly impacts not only the chemical purity of the material, but also its thermal stability and resistance to moisture.

Overall, charcoal offers superior reactivity but suffers from handling and stability issues, whereas agglomerated biocarbon provides operational robustness at the expense of reduced reactivity. One way to compensate for the lower reactivity of agglomerates is to reduce the final particle size, thereby shortening diffusion distances and increasing the available reactive surface area. In practice, agglomerate development requires balancing multiple properties,

including reactivity, mechanical strength, thermal stability, impurity levels, and moisture resistance. The optimal solution represents a compromise between these factors, while remaining cost-effective for industrial use.

5. Conclusion

This work presents industrial experience with the introduction of biocarbon in silicon furnace operation and demonstrates that stable operation is achievable at substitution levels exceeding 50% of the carbon demand. This was validated on a 17 MW furnace without long-term loss of average silicon yield.

The work further demonstrates that successful implementation depends not only on material properties but also on operating practices. The structured qualification methodology and transition from reactive to controlled operation were essential for achieving stable furnace performance.

The comparison between charcoal and agglomerates highlights the trade-off between reactivity and handling strength, emphasizing the need for optimized material selection and properties.

Continued research and development, both in-house and in collaboration with universities, research institutions, and industry partners, strongly supports Wacker Holla in progressing toward its climate goals.

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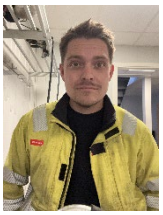

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