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Industrial experience of using biocarbon briquettes in FeSi production process

Denys Gryshan[1,2], Maria Wallin[2], Mykola Yermolov[1], Jaroslav Legemza[3], Nataliya Korol[4], and Gabriella M. Tranell[2]

[1]OFZ, a.s., Široká 381, 027 41, Oravský Podzámok, Slovakia, gryshan@ofz.sk
[2]Department of Materials Science and Engineering, Faculty of Natural Sciences, Norwegian University of Science and Technology, Trondheim 7491, Norway, gryshan.denys@ntnu.no
[3]Faculty of Materials, Metallurgy and Recycling, Technical University of Košice, Letná 1/9, 042 00 Košice, Slovakia, jaroslav.legemza@tuke.sk
[4]Perechin timber and chemical plant, 25, Uzhans'ka st., Perechin, Zakarpatska region, Ukraine, korolni@lxk.com.ua

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Abstract – Substitution of fossil carbon by bio reductants such as charcoal is one of the prioritized directions for sustainable development of the high silicon alloy (MG-Si and FeSi) production process. The fines fraction created during the production of charcoal could potentially be effectively utilized in a traditional metallurgical submerged arc furnace (SAF) in the form of agglomerates. Compared with lumpy charcoal, agglomerates such as pellets and briquettes show several advantages, including lower moisture absorption and lower fragility which means reduced dust formation. In addition, their higher density improves logistics and utilization efficiency. Additional costs brought by the use- and processing of bio-reductants may be compensated by a decreased CO_2 emission cost.

Based on available laboratory-scale data, the differences in properties between agglomerates and lumpy materials are not expected to significantly affect the SiO reactivity of the carbon charge. Accordingly, potential deviations in furnace operation and energy consumption may be due to other factors such as thermal stability, charge density etc.

The aim of this work was to analyze available operational data of the behavior of an industrial 23MVA submerged arc furnace producing FeSi75 at OFZ during a 20-shift trial, using biocarbon charcoal briquettes as a partial replacement for fossil reductant. The briquettes were produced by the Perechin plant, using cornstarch as binder. Results indicated similar Si-yield, energy consumption and product composition for the charcoal briquettes as with a typical carbon mix, thereby opening the path towards an increased utilization of charcoal fines and a more robust approach towards cost-efficient carbon neutrality in FeSi production.

1. INTRODUCTION

OFZ, a. s., is manufacturer of ferroalloys based in Slovakia, with a history dating back to 1952. For over 70 years, the company has produced a wide range of alloys based on reduction smelting in submerged arc furnaces (SAF). These include chromium-based ferroalloys (FeCr LC, FeCr HC), manganese-based (FeMn HC, FeMn MC, FeSiMn), silicon-based (FeSi) and a wide range of other specific alloys (FeMo, FeW, FeSiAl, FeSiTi, FeTi, SiZr etc).

The production site has 7 submerged arc furnaces with a total capacity of more than 100, 000 tonnes of alloy per year. Current operation includes two furnaces for manganese-based alloys, four for silicon-based alloys and one smaller furnace for refining and remelting of fines. In 2018, one of the SAF's was modernized for the possibility to produce Si metal.

Today, the most in-demand and competitive products for OFZ are concentrated around various types of FeSi, FeMn, FeSiMn, and FeSiCa alloys, as well as cored wires. OFZ is the last producer of FeSiCa in Europe due to the company's developed approach to switching the production process between FeSi and FeSiCa. However, the current situation in the local electricity market, compared to other production sites in the world, has not supported maintaining stable production volumes over the last few years. Nevertheless, development of long- and short-term solutions for improvement of production processes and decreasing Greenhouse Gas (GHG) emissions are part of the company's strategy. The use of biocarbon as a substitute for the fossil reductant is one of the promising short-term paths to reduce direct emission from ferroalloy production processes.

The specific ferroalloy production process is typically tuned towards different mechanical, thermal, chemical and electrical properties of the reductants and to some extent oxidic raw materials. Plant metallurgists evaluate the effects of different raw materials on the production process by analysis of available data from the furnace management system and the company's ERP (Enterprise Resource Planning) system Karat.

The traditional charge for MG-Si and FeSi alloy SAF operation is lumpy material (Schei et al., 1998). Permeability of the charge mix (Tranell et al., 2010), is a significant aspect both for the silicon-producing reactions and furnace safety.

The selection of reducing agents for the ferrosilicon production process requires consideration of several criteria, such as economic considerations, appropriate chemical composition (low ash, high reactivity, low volatile substances, high fixed carbon, etc.), high electrical resistance, appropriate granulation, and high mechanical strength. Compared to coke, semi-coke, and industrial coal, charcoal has lower thermal abrasion strength, low sulfur, and phosphorus content, high moisture content, low mechanical strength, higher reactivity and higher electrical resistivity (Etemadi et al., 2023). Higher SiO-reactivities (Myrhaug et al., 2004) of bio reductants in Si/FeSi process compared to fossil reductants may also decrease the power consumption (Junru et al., 2018) in addition to decreasing direct CO_2 emissions (Smith-Hanssen et al., 2023).

In the current work, a twenty-shift trial period producing FeSi75, using up to 38% Cfix equivalent of charcoal briquettes in the charge mix will be compared with two typical periods using only fossil reductants. Performance indicators such as silicon yield, specific energy consumption and product composition will be evaluated along with effects on furnace operation. Results from this work create a baseline for the use of composites/agglomerates in SAF production process, which will be further explored together with partners in the EU Horizon Europe project QUEEN (Quartz Enrichment Enabling Near-Zero Silicon).

2. PRODUCTION AND TESTING OF BIO-C BRIQUETTES In FeSi75 PRODUCTION

The main practical aspect of using agglomerated materials in the ferroalloy furnace is the possible disintegration of the briquettes before reaching the main reaction zone. Such disintegration decreases the Si yield, loses unreacted carbon to the off-gas dust and may affect the silica fume quality. Low temperature decomposition of an organic binder could affect reactivity of the charge and strength of lumps. Fines generation related with high temperature properties of agglomerates can affect furnace gas flow and pressure drop in charge (Ringdalen et al., 2022). Performance of the agglomerates in the charge and their effect for furnace performance in the case of partial replacement of fossil carbon was subject for investigation with assumption overall permeability of the charge could be maintained by other components of the charge, primarily quartzite and wood chips.

2.1 SAF

The trials were performed in furnace No 23 for production of silicon-based alloys (Klocok et al., 2021). This SAF has a semi-open construction and self-baking electrodes. The annual capacity is 15, 000 tonnes of FeSi. The parameters of the furnace are presented in Table 1 below.

Table 1. SAF parameters

Installed capacity, MVA	Diameter of electrodes, mm	Pitch Circle Diameter, mm	Diameter of bath, mm	Bath depth, mm
22,8	1200	2900	6000	2400

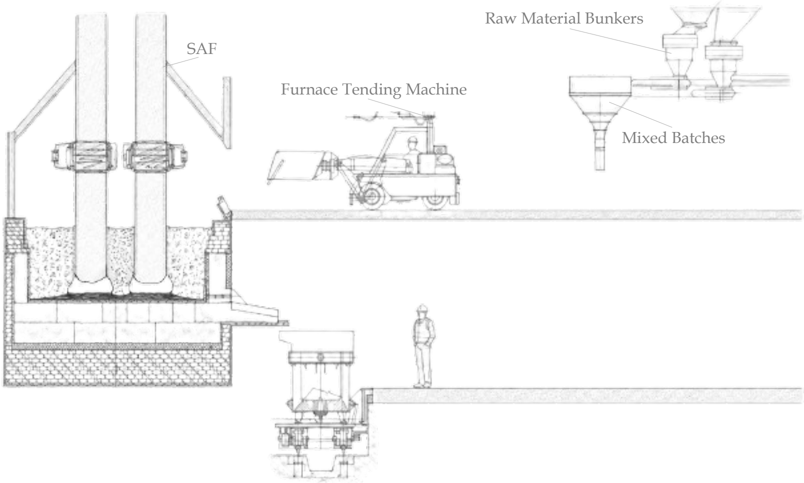

Figure 1. Schematic overview of furnace charging system

The furnace charging (Figure 1) is done batchwise by using a furnace tending machine. The different raw materials have separate bunkers above the loading area. Based on required recipe, a specific volume of each raw material is moved to the mixed batches bunker situated close to the uploading area. A furnace tending machine moves batches into the furnace.

2.2 Raw materials properties

The types and composition of the main charge components to produce FeSi in the studied periods are shown in Figure 2, Table 2 and Table 3.

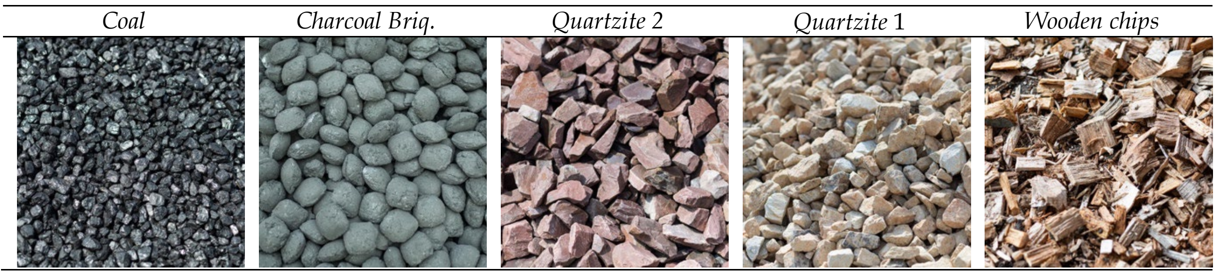

Figure 2. Main raw materials for FeSi production

Table 2. Chemical composition of quartzite sources (wt%)

Name	SiO_2	P	FeO	Al_2O_3	CaO	TiO_2	MgO	LOI
Quartzite 1	98.92	0.024	0.09	0.42	0.08	0.05	0.001	0.22
Quartzite 2	98.08	0.013	0.11	1.06	0.08	0.064	0.007	0.44

Table 3. Chemical composition of different carbon sources (wt%)

Name	Ad	Va	P	Al_2O_3	Cl	S	SiO_2	CaO	MgO	FeO
Coal	4.25	33.2	0.004	0.56	0.13	0.46	1.57	0.62	0.040	0.57
Charcoal 0-6 mm	4.00	12.63	0.052	0.50	0.06	0.03	0.2	0.7	0.019	0.08
Charcoal briq.	4.67	16.79	0.077	0.06	0.006	0.03	0.34	2.08	0.019	0.07

Va - Volatile matter content, air-dried basis
Ad - Ash content, air-dry basis

The measured SiO-reactivities of the carbon materials are listed in Table 4. As seen from the table, coal demonstrated lower reactivity than the charcoal, which is in agreement with published data (Jayakumari and Ringdalen, 2022) and practical experience of the authors.

Table 4. SiO-Reactivity of used carbon materials

Name	Coal	Charcoal (prior to briq.)	Charcoal briq.
SiO-Reactivity, ml SiO (SINTEF test)	771	530	534

2.3 Production of Charcoal Briquettes

Charcoal is a solid product of the high temperature pyrolysis of wood biomass. The Cfix content of charcoal, which depends on the pyrolysis temperature and is affected by the physical properties of the wood, typically ranges from 80 to 85 wt%. The volatile content in charcoal is typically 5–20 wt%, and ash content, which depends on the content of minerals in the wood material, is approximately 0.2 to 5 % (Legemza et al., 2019)

Briquetting an agglomeration and densification technology, is one of the technologies used to improve the quality of biomaterials (Lomunyak et al., 2024). Charcoal fines briquetting is a sustainability-oriented approach that allows transforming small charcoal fractions, which are difficult to use efficiently in loose form, into a stable, valuable, and marketable biocarbon material. As such, briquette production reduces raw material losses, improving resource efficiency, and creating added value from side stream of charcoal production.

The quality of a charcoal briquette depends on a combination of factors. These include the particle-size distribution of the charcoal, the type and concentration of binder, the moisture content of the mixture, the pressing method, and the drying regime. A key element of briquette production is the binder system. The binder must hold the charcoal particles together, but at the same time it should not significantly increase ash content or make the product too expensive. Available research (Pahnila et al., 2026) shows that starch-based binders are promising based on their properties and possible scalability. As outlined above, agglomeration could significantly increase the value of fine charcoal fractions which will allow its use in standard SAF operation. At the same time, agglomerated material could reduce fines generation during handling, packaging, transport and storage. This is especially important for a plant with an internal logistics line which was built for the more mechanically durable coal.

Figure 3. Charcoal briquettes with cornstarch binder used in trials

The briquettes in the study, illustrated in Figure 3, used cornstarch as binder and were produced by Perechin timber and chemical plant in the Ukraine. Cornstarch was chosen as a binder due to its cold strength characteristics and market availability (Yankovych and Korol, 2025). Charcoal fines with a particle size of 0-6 mm were used to produce the targeted briquette size of 52 × 52 × 30 mm. A mixture of charcoal, hot water, and 10 % binder is fed to the briquette press. The amount of added water depends on the initial moisture of both the charcoal and the binder. Briquettes are formed in industrial roller compactor with 300 mm patterned rollers and working pressure of 100 MPa. After compaction, the briquettes are transferred to the drying system. The drying unit contains three sequential temperature zones, with temperatures gradually decreasing from 120°C to 70°C. Gradual cooling prevents cracking and ensures stable mechanical strength of the final briquettes.

2.4 Trial Procedure

The approach for testing of briquettes in FeSi75 production was based on previous experience using lumpy biocarbon (20-70 mm) in the same production process. Stable operation with up to 38% lumpy charcoal of total Cfix in the charge mix had been achieved and hence, for the current trials, we set the same level of substitution. Trials were started with a base mix (only fossil reductant) in both reference periods (Ref.1 and Ref.2) as well as in the briquette trial period. The briquette fraction in the trial period was increased with each shift until achieving a Cfix fraction from briquettes of 20, 30 and 38% accordingly.

3. RESULTS AND DISCUSSION

The furnace performance and the operation during the reference and trial periods were assessed from several points of view;

- Furnace productivity
- Metal and silica fume quality
- Si yield
- Cost-effectiveness including effects of CO_2 pricing

3.1 Productivity

The SAF productivity for each of the three production periods with equal duration – 20 shifts, is presented in Figure 4. The average performances (MWh/tonne alloy) for each period are illustrated with dotted lines for comparison. The absolute difference between highest and lowest average performance in the different periods is around 3.1 %. It should be noted that reference periods Ref. 1 and Ref. 2 were monitored after a long interruption of the furnace, which could have affected the productivity in those periods. There were also several short-term interruptions due to maintenance. However, as seen from the figure, the productivity in the period using a mixed briquette/fossil charge is not significantly different to a pure fossil charge.

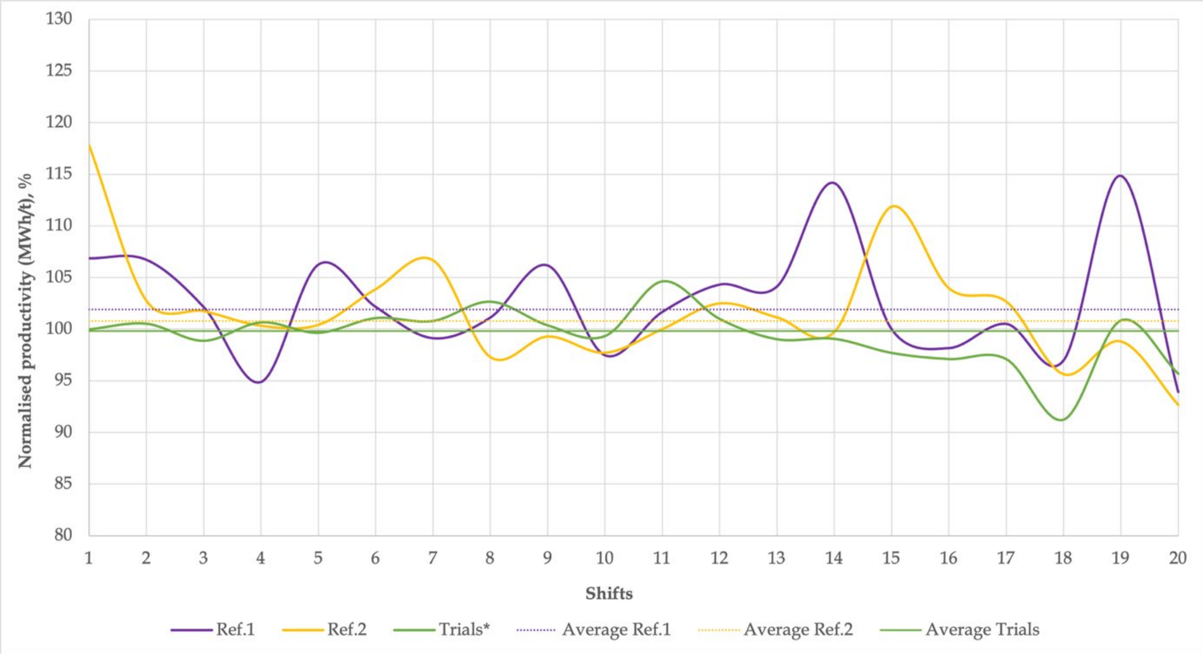

Figure 4. Normalised productivities of the SAF 23 during reference periods and trials with briquettes

During each period, 89 to 99 samples of the FeSi metal were analysed, results plotted in Figure 5. The standard deviation (σ) in average quality of FeSi (Si content 75 wt%) across all periods is 1.04 wt.%, and without any consistent difference between a fully fossil and a mixed bio-C/fossil charge.

Figure 5. Variation in quality of the FeSi with average lines during investigated periods based on analysis of 89-99 samples in each period.

3.3 Metal and fume quality

The average quality of the FeSi metal for each period is presented below in Table 5.

Table 5. Average quality of the metal during investigated periods (in wt.%)

Period	Al	C	Ca	Cr	Fe	Mn	P	Si	Ti
Ref.1	1.52	0.20	0.68	0.10	22.65	0.23	0.03	74.18	0.11
Ref.2	1.12	0.08	0.54	0.09	22.25	0.21	0.03	75.11	0.12
Trials	0.72	0.07	0.25	0.09	23.02	0.24	0.03	74.88	0.11
Typical tolerance [OFZ, FeSi]	1.60						0.035	73.50	

The average quality of silica fume for each period is presented below in Table 6. There is no continuous measurement of the off-gas dust volume and quality in the furnace. Silica fume is collected in silos, densified, and then analyzed during packing. During each comparative period, from 5 to 7 samples of the fume were analyzed.

Based on the silica fume composition achieved for the different trial periods, we conclude that they all fulfill the requirements of both certified qualities of silica fume (Class 1-2 and Microxil) mentioned in Table 6 below.

Table 6. Average quality of the off-gas dust silica fume during investigated periods (in wt.%)

Period	Al_2O_3	C	Cl	Fe_2O_3	K_2O	Na_2O	MgO	SiO_2	CaO	Na_2Oeq
Ref.1	0.78	2.33	0.18	3.01	0.70	0.11	1.46	88.21	0.93	0.57
Ref.2	0.39	2.61	0.20	1.41	0.69	0.14	1.62	91.19	0.70	0.59
Trials	0.25	2.47	0.27	1.69	0.80	0.16	1.65	89.92	1.16	0.69
Typ. tolerance [OFZ, by-products] Class 1-2			0.30					85.00	1.00	6.00
Typ. tolerance[OFZ, by-products] Microxil			1.80					80.00	3.50	8.00

3.3 Si yield

The Si yield during the trial period has been analyzed by mass balance to recognize possible C-losses and for comparing average numbers from other periods. The amount of SiO_2 contained in the ash of the carbon materials was also taken into consideration in the mass balance. We can see somewhat lower average yield during the trials compared with the two reference periods in Table 7. At the same time, inside the trial period the Si-yield was increasing gradually from 84.3 in the beginning of the trial to 89.4 % at the end. The lower yield in the beginning of the trial period could be a consequence of adjustments to the furnace operation. The off-gas dust amount did not increase during the trials. The Si yield numbers do not include metal retained in the sculls. This middle-product can be used as raw material in the production of FeSiMn or alternatively, metal from the sculls could be separated from slag through different technologies (Gryshan and Kulish, 2015) for more efficient usage.

Table 7. Si-yield during investigated periods

Period	Ref.1	Ref.2	Trials
Si-yield, %	87.46	86.91	85.30

3.4 Cost-effectiveness

To estimate relevant production costs for different charge combinations, we have calculated the amount of all raw material consumed during each production period. These volumes have been connected to actual furnace productivity and prices of raw materials. Cumulative charge mixes used in each period are presented in Figure 6. The ratio of different carbon materials in the charge is presented in Figure 7.

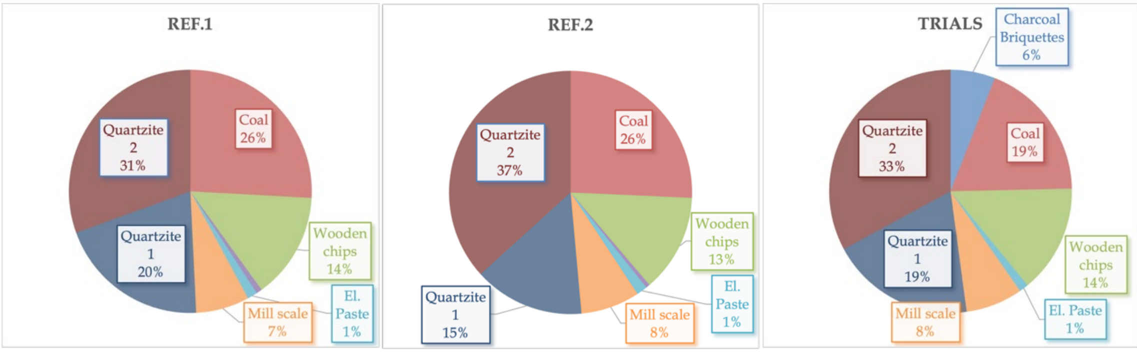

Figure 6. Cumulative charge raw material composition during investigated periods (in wt%)

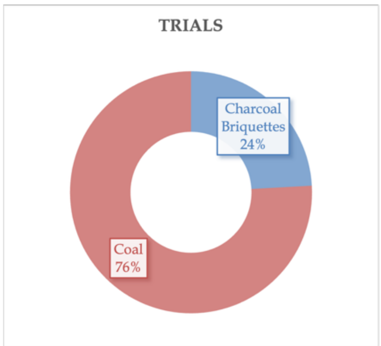

Figure 7. Average wt.% of biocarbon usage during trials

Direct emissions (scope 1) were calculated based on the consumed raw materials and their respective emission factors, following the company procedure in accordance with regulation (EU) 2018/2066. During the substitution trials, direct emissions have decreased 25.8 % compared to periods using fossil reductants as shown in Table 8.

Table 8. Calculated direct CO_2 emissions during investigated periods

Period	Ref.1	Ref.2	Trials
Direct production emissions, tCO_2e	3.02	3.03	2.24

The relative production cost per unit metal is compared in Figure 8. As shown in the figure, the total cost stayed almost the same for the part-briquette charge as for the fully fossil charge, using the price of carbon permits at a current level of 75 €/t (Trading Economics. EU Carbon permits). For instance, extrapolating the calculations to a hypothetical scenario in which 50 wt.% of the fossil reductant is replaced with biocarbon indicates that the raw material cost per tonne of alloy would increase by approximately 10%. However, the total unit production cost, including carbon permit costs, would increase by only about 2% compared with the reference case. Furthermore, the share of carbon permit costs in the total production cost would decrease to approximately 7%.

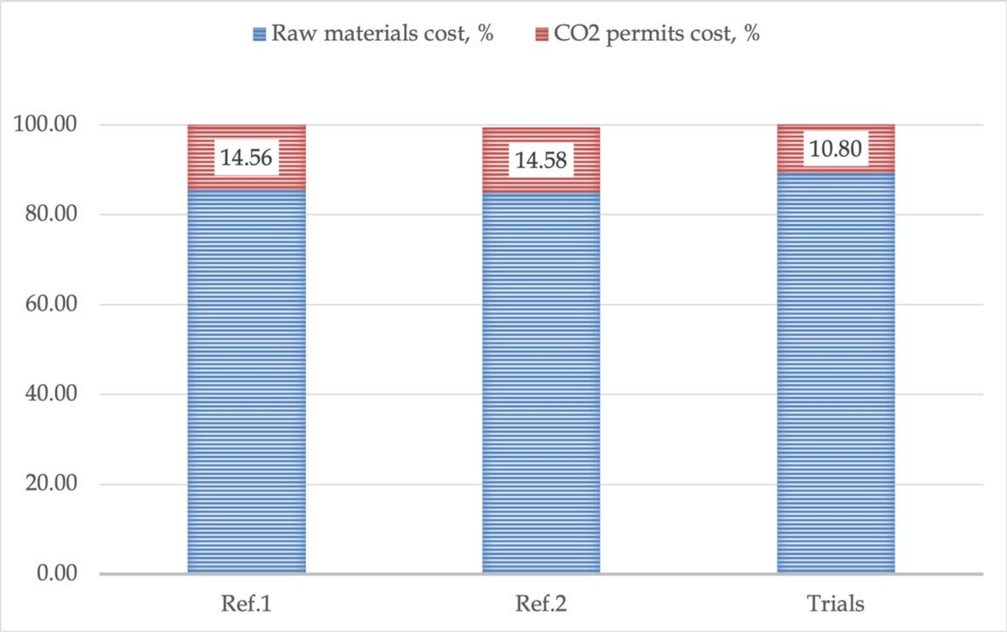

Figure 8. Relative unit production cost and CO_2 in cost structure

The main reason for these results is the significant difference in price of fixed carbon in bio- and fossil reductants, as indicated in Figure 9.

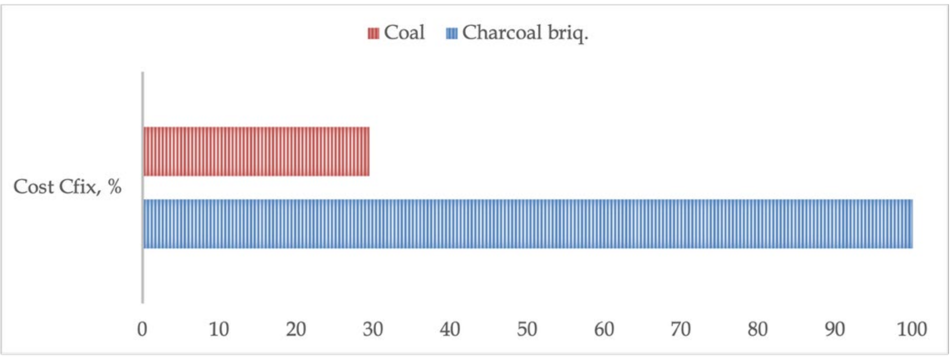

Figure 9. Normalised Cfix cost in coal and charcoal materials

The wider implementation of biocarbon materials in Europe will be driven mostly by price, availability of the required volumes, stability of the quality of reductants, as well as emission restrictions. CO_2 permit quotas will likely be reduced for most European companies using bio reductant. This is unfortunate as it does not stimulate producers to use the more expensive biocarbon reductants.

4. CONCLUSIONS

The trials described in the current work show that biocarbon briquettes, made from bio-carbon fines, meet the requirements of quality for use in the SAF at OFZ producing FeSi75.

The silicon yield during briquette trials have been recorded at a level of 84.3-89.4 % with an average of 85.3 %, which generally corresponds with the yield in production periods with fossil carbon usage. For more precise analyses of C-losses in the off-gas, real-time measurements should be carried out.

The difference in average furnace productivity (MWh/tonne alloy) across the studied reference- and trial periods is 3.1%. The total number of quality control samples can be considered statistically sufficient to assess the process deviation. The results indicate that productivity variations in the briquette period are similar to those of the fossil periods. The metal and silica fume qualities both pass the requirements of OFZ´s product specifications. Additionally, the production cost, taking into account CO_2 cost, are similar for a fully fossil charge and a partly substituted briquette charge. In addition to other parameters measured during the trials, the off-gas should be further investigated to determine the composition of volatiles and their interaction with the charge during a longer time period

Logistic adaptions may become important for the use of biocarbon at scale. Charcoal is more fragile than coal/coke, which can affect the generation of the fines and an increasing possibility of self-ignition. Ideally, biocarbon/charcoal should hence be minimally handled/transported before entering the SAF. Whether this fragility applies to the same extent to briquettes is still unknown as briquettes showed better cold strength/durability compared to charcoal lumps. Hence, these materials may better suit the standard logistic scheme built for fossil carbon materials.

5. ACKNOWLEDGMENTS

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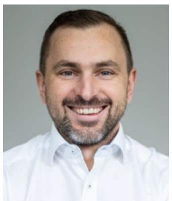

Denys Gryshan
Innovation Project Manager, OFZ, Slovakia
PhD Candidate, NTNU, Norway

Hold an M.Sc. from KTU, Kryvyi Rih. With 15+ years of experience in the ferroalloys industry. Expertise includes realization of investment projects, ore beneficiation, sensor-based sorting technologies, by-products valorization and REACH. Actively involved in innovation projects for manganese and silicon alloys under Horizon Europe Programme.