Chemical package solutions for carbon footprint reduction in EAF steelmaking

The green steel revolution is progressively shifting crude steel production from BF-BOF technology to scrap-DRI electric arc steelmaking, promising a considerable reduction in the greenhouse gas emission footprint from 1600-2200kg CO2/ton of crude steel to less than 900kg CO2/ton. There is still a lot of scope for optimization and further reduction of carbon dioxide emissions in the EAF by adopting the best available injection technologies readily available. Substitution of hydrogen for gaseous fossil fuels is a long term solution, where many R&D efforts are being concentrated. This will be ready in the next few decades, when green hydrogen will become a commodity, distributed in integrated networks and available at competitive prices.

Zero-emission EAF steelmaking is however far from being achievable in the medium term. Carbon injection will stay indispensable for many years to come, key to slag foaming and crude steel refinement. For this reason, our many efforts have been concentrated in the past few years on fine tuning injection technology by adopting carbon neutral sources, in the form of polymeric pellets obtained from waste recycling, or derived from biological renewable resources.

INTRODUCTION

MORE Company boasts the experience of more than three decades in mastering the chemical energy in EAF steelmaking, tackling the challenge of carbon footprint reduction for the next future. We are continuously investing into R&D projects to improve the efficiency of our products, focusing on the reduction of specific energy consumption and enhancing EAF productivity. M-ONE injection technology integrates three functions into one tool: efficient burner heating, deep carbon dosing for slag foaming, and high-speed oxygen concurrent injection for decarburisation.

In EAF steelmaking, the reduction of emissions starts from with responsible and efficient use of conventional resources. Compared with the state of the art, a lot of fossil fuel is still wasted in many EAF applications. Most feature obsolescent technology, but many are brand new, supplied by low-cost suppliers, who are sacrificing long-lasting efficiency for short-term convenience of capital expenditure. From the outset, MORE has developed fuel and oxygen valve stands that integrate air purging and provide maximum flexibility in use. The higher complexity is paid back quickly from fuel and oxygen savings.

Continuous improvement of these technologies has led MORE to develop a patent pending technology for the full control of gaseous fuel and oxygen that combines the efficient use of utilities with reliability of the equipment. The adoption of hydrogen-rich fuel gas mixtures is already a proven reality in many plants, reusing the available coke oven gas as a by-product of blast furnace operation. R&D projects in cooperation with distinguished labs and qualified universities are already underway to be ready for safe industrial applications as soon as green hydrogen is available in grid distribution in the next few decades.

At the present stage of development, we are still focusing on the optimisation of oxy-hydrogen flame kinetics. Laboratory prototypes are currently under extensive testing as a preparatory stage for the first industrial protype in the rush for the 2030 transition to green steel. It is our vision that carbon will remain essential for the EAF process in the near future, fundamental for foaming slag and steel refinement. The replacement of fossil carbon sources such as petcoke, anthracite, or coal, with bio char, or recycled polymer is a more realistic ambition in the medium term.

MORE is a forerunner in foaming slag technology. The company has participated in many industrial projects by applying recycled polymers and carbon mixtures as slag foaming media, while also holding many patents in this application field. The knowledge gained has allowed MORE to evolve and refine polymer injection technologies to offer reliable and flexible solutions to integrate with specific feedstocks that are locally available from the circular economy.

EFFICIENT INJECTION EQUIPMENT: M-ONE TECHNOLOGY

The M-ONE unit is an ALL-IN-ONE integrated injector with three independent functions that can be individually controlled: a premixed swirled flame burner, high momentum supersonic oxygen injection, and coherent high speed coal injection (*Figure 1*). The M-ONE injector fits into special bulged boxes (*Figure 2*), specifically designed to install the units through the EAF wall, very close to the bath. Reducing tip-to-bath distance is crucial for enhancing the efficiency of the injector across all three functions described earlier.

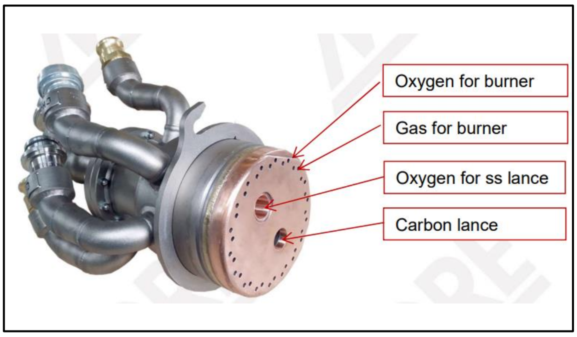

Fig 1 **M-ONE Integrated injector**

Fig 2 **M-ONE assembled in a bulged block**

The most relevant technical advantage of the M-ONE injector is the ability to concurrently inject supersonic oxygen and coal in the same place (*Figure 3*). The high-speed oxygen jet exits the nozzle at Mach 2.2 to 2.4. It drags and accelerates the coal particles into the slag at exactly the same spot at which oxygen impinges. The M-ONE injector allows for higher coal penetration into the slag and an immediate reaction between the iron oxide produced by the oxygen and the carbon. Carbon monoxide produced by the reaction between iron oxide and carbon at the interface between the slag and the liquid steel enhances the foaming and prevents refractory decarburization, thus protecting the bricks from premature wear and tear. High efficiency injection enables a consistent reduction in coal consumption and consequently a reduction in carbon dioxide and emissions to the dedusting plant.

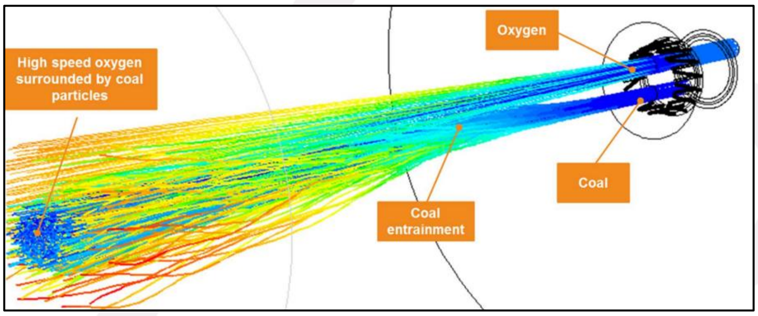

Fig 3 **Concurrent injection: solid particles and supersonic oxygen synergy**

The flame is integrated in the M-ONE tip by an enveloping high-speed oxygen and coal stream. The burner nozzles are designed to intimately mix fuel and oxygen, preventing losses. They produce a high temperature flame (> 2200°C) with a wide surface able to transfer the highest heating power to the metallic charge in the shortest possible time. A mixed swirled flame is shown in *Figure 4*.

Fig 4 **M-ONE Mixed Swirled Flame (MSF)**

ACCURATE AND RELIABLE REGULATION WITH ZERO LOSSES: FULL CONTROL VALVE STANDS

There is a widespread lack of knowledge about how important reliable and accurate regulation of gas media is for EAF performance. International standards and regulations cover safety aspects concerning firefighting and explosive atmosphere hazards, but they are only a starting point, not enough to guarantee efficient operation.

Having had the privilege of servicing many plants, MORE realised that scarce consideration is applied to regulating valve trains, sometimes equipped with low quality instrumentation, the accuracy of which drifts over time. Recurrently, the valves miss the position feedback, the lines are unfurnished with pressure monitoring and the rooms ignore the basic rules for automatically locking the equipment and venting in case of emergency. We are conscious that gaseous media regulation in an EAF calls for very specialist expertise and knowledge. For this reason, we enhanced the automated control package with several diagnostic functions to keep the system in perfect condition and schedule any required maintenance operations in advance.

A specific focus has been placed on keeping the burner nozzles clean over time. Most existing applications use the same media to purge burners, a practice usually called “low flame”, or “purging flame”. Beside the intrinsic unsteadiness associated with using large sized regulating valves to control low flows, this approach wastes a lot of fuel and oxygen over long periods of time when they are not required for melting or steel refining purposes. From the outset, MORE has conceived and applied an air purging function for its valve racks. Fuel gas and oxygen are used only for technological purposes and not wasted for ancillary purposes. Compressed air is applied for nozzle purging, whenever the technological gases are not required for production. Steelmakers must realise that the operating expenditures related to the purging flame practice are relevant and long-lasting (*Table 1*). Many competitors offer primitive technological solutions with lower capital expenditure, minimising the role played on operational expenditure by accuracy in regulation performances.

Furnace capacity	100	t		
2nd oxygen flow rate	200	Nm3/h		
primary oxygen flow rate	200	Nm3/h		
gas flow rate	150	Nm3/h		
P-on	45	min		
P-off	15	min		
TtT	60	min		
Burner time	15	min		
Oxygen injection time	22.5	min		
Burner purging time	45	min		
Injection purging time	37.5	min		
Number on injectors	3			
average heats per day	24	heats/day		
operational days per year	300	days/year		
heats per year	7200	heats		
oxygen cost	0.170	€/Nm3		
natural gas cost	0.450	€/Nm3		
compressed air	0.015	€/Nm3		
oxygen consumption for purging	825	Nm3	140.3	€
specific purging oxygen consumption	8.25	Nm3/t	1.403	€/t
compressed air for oxygen purging	825	Nm3	12.4	€
specific compressed air for oxygen purging	8.25	Nm3/t	0.124	€/t
oxygen savings			127.9	€
specific oxygen savings			1.3	€/t
one year oxygen savings			920 700 €	€
natural gas consumption for purging	337.5	Nm3	151.9	€
specific purging natural gas consumption	3.375	Nm3/t	1.519	€/t
compressed air for natural gas purging	337.5	Nm3	5.1	€
specific compressed air for natural gas purging	3.375	Nm3/t	0.051	€/t
natural gas savings			146.8	€
specific natural gas savings			1.5	€/t
one year natural gas savings			1 057 050 €	
specific savings			2.7	€/t
one year total savings			1 977 750 €	€

Table 1 **Savings achieved by purging using air**

The latest evolutions in valve rack design led MORE to apply a full control concept to the gaseous media, a patented technology controlling flow rates in every operating condition, self-adapting to variable situations and enhancing the robustness and flexibility of the application (*Figure 5*). Extensive digitalisation, with advanced diagnostics built into the firmware, monitors operations and predicts maintenance actions when required. Warnings, trips, or drifts in performance can be anticipated. The valve control stands accurately regulate the gases, eliminating all inefficiencies relating to unnecessary use of these gases during non-productive time. This reduces the emissions footprint of steel production and makes possible obtaining green and white certificate credits where available (*Table 2*).

Fig 5 **MORE Full control Valve Trains (Celsa Group)**

CO2 produced by purging flame	337.5	Nm3	
	3.375	Nm3/t	
	662.9	kgCO2/heat	
	6.629	kgCO2/t	
	4773	tCO2/year	

Table 2 **CO_2 emission savings by purging air**

HYDROGEN AS A SUBSTITUTE FOR GASEOUS FOSSIL FUEL FOR HEATING

There is huge expectation in the steel industry that hydrogen gas will be a substitute for fossil fuels to for zero emissions steelmaking. However, in EAF steelmaking only 2 to 10% of green house gas emissions are related to the use of fuels for direct heating of the charge (*Figure 6*). The largest proportion of emissions are related to steel decarburisation and slag foaming; processes in which the role of carbon will play a central role for many years to come.

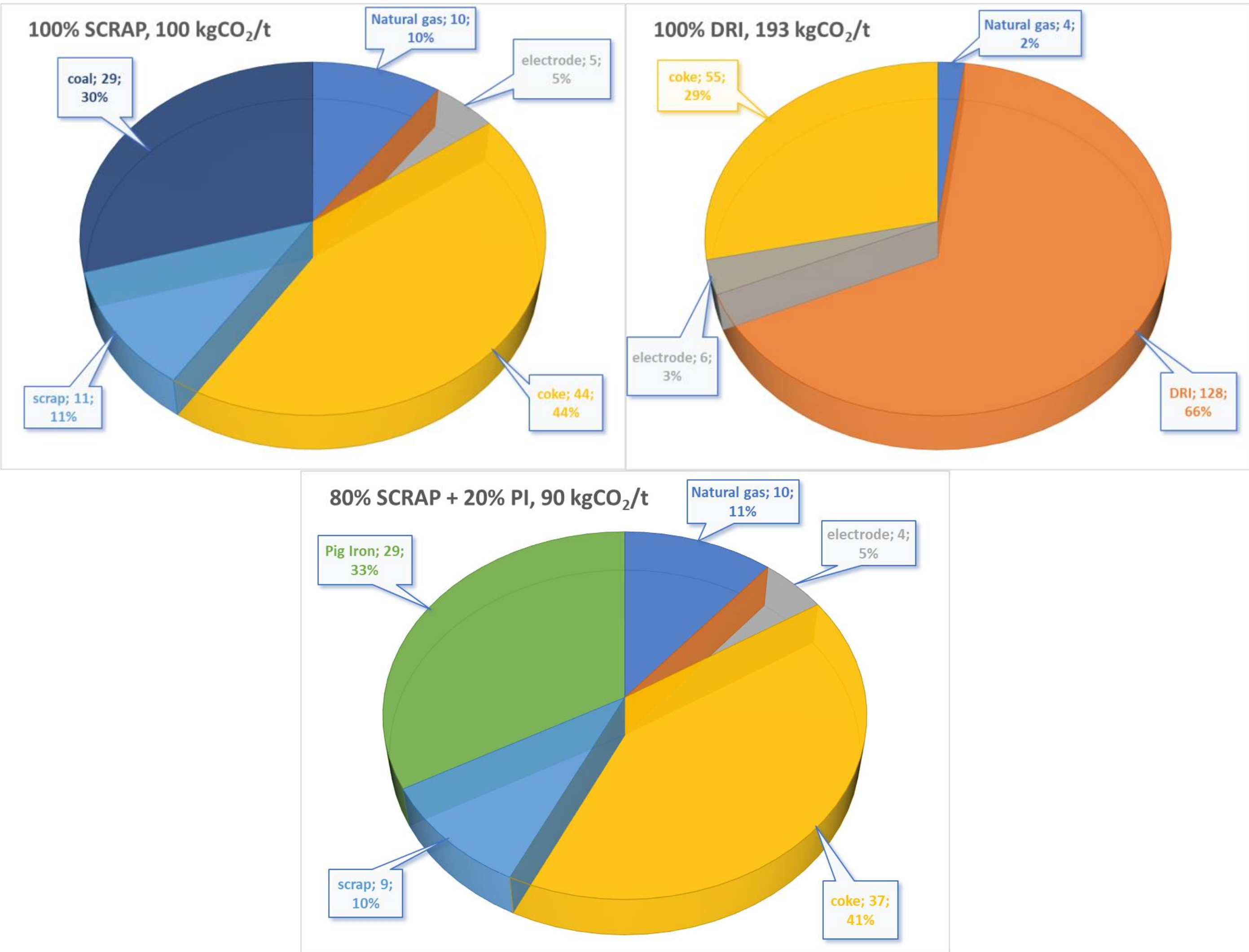

Fig 6 **CO_2 EAF emissions for different charge mixes**

The use of hydrogen rich gaseous fuel mixtures is not new in our industry and there are already many applications using Coke Oven Gas (COG) as a gaseous fuel for oxygen burners, in electric arc furnaces processing hot metal (*Figure 7*). COG is a by-product of the blast furnace with a typical composition, as shown in *Table 3*.

	Typical	Shanghai no. 5
H_2	50-60%	59%
CH_4	20-35%	25.5%
CO	5-10%	6%
C_2H_4	1-5%	2.3%
CO_2	0-10%	6%
N_2	0-7%	4%
LHV	5 kWh/Nm^3	

Table 3 **COG composition**

Fig 7 **COG regulating valve train, Baosteel Shanghai No. 5 Steel Co. Ltd. (Baoshan, Shanghai, China)**

Pure hydrogen as a fuel can easily be adapted to current burner design and regulation technology. It is already used in many industrial applications, such as bright annealing of stainless coils and for small sized torches. Prototypes and industrial scale test rigs for the glass industry have already proved industrial feasibility. Our R&D projects, carried out in collaboration with distinguished university specialists and respected laboratories, have already completed the pre-industrial stage of development. The kinetic data collected will be used for flame modelling in the burner design stage. The industrial prototyping stage will be completed before mid-2024.

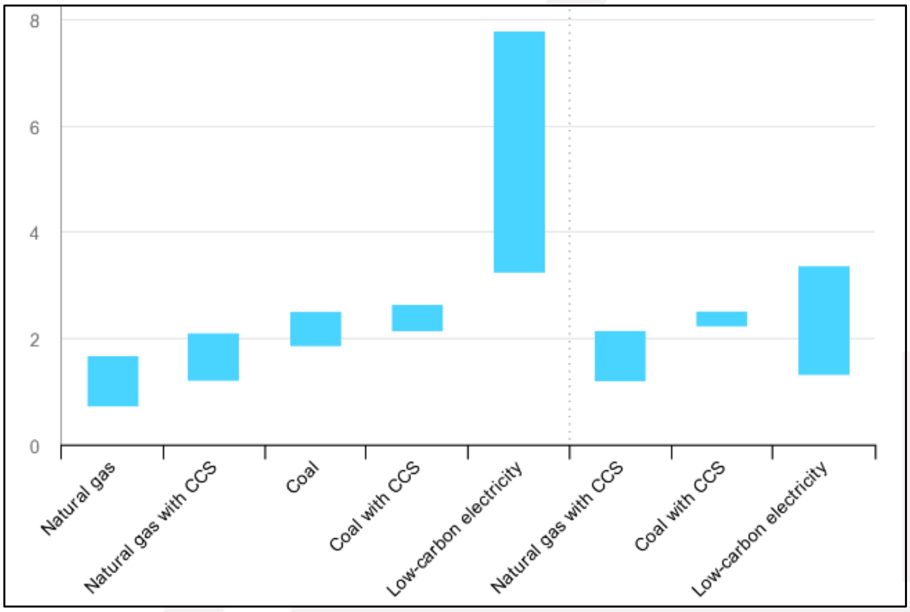

Fig 8 **Hydrogen production cost by energy source and technology [1]**

Alongside burner flame design and hazard management of regulation equipment, the main limiting factor is currently hydrogen availability, as a commodity at commercially viable prices (*Figure 8*). Green hydrogen is currently very expensive and produced only in limited quantities. Nowadays, the only hydrogen available at competitive prices is still mostly syngas, produced using natural gas reformers, via hot catalysis from fossil fuels. Water hydrolysis supplied with renewable electric energy is under development, supported by consistent institutional funding. Future cost projections anticipate an equalisation with the actual cost levels of fossil fuels for very long-term investments, but only if supported by electrical energy costs that are three to five times lower than the current commercial prices (*Figure 9*).

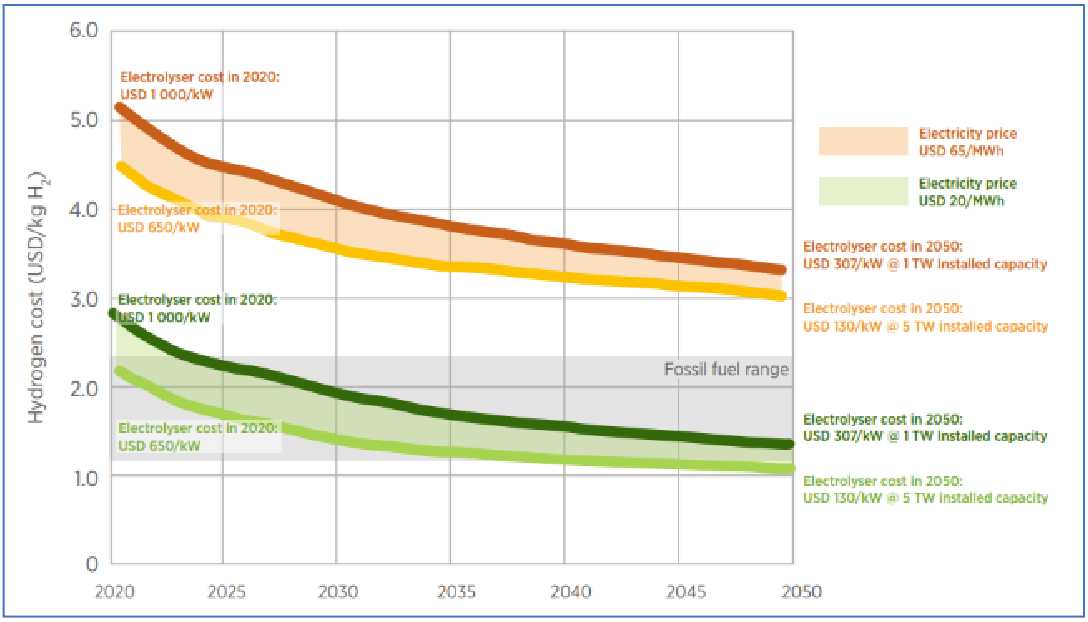

Fig 9 **Cost of green hydrogen produced by electrolysers of different sizes: different electricity prices projections [2]**

FOSSIL COAL SUBSTUITUTES FOR CARBON NEUTRAL INJECTION

A large part of EAF green house gas emissions come from carbon charged to the process, or coke injection. The foaming slag process and the reduction of FeO produced by liquid steel decarburisation, are fundamental to electric arc steelmaking. The underlying chemical physical mechanisms driving the process kinetics call for solid carbon to be injected into the slag. Extensive substitution with hydrogen gas is not viable.

For many years, research has concentrated on substituting more sustainable materials for metallurgical carbon, which is usually produced from bituminous petroleum or anthracite. Two main categories of carbon sources have been investigated: the reuse of by-products obtained by end-of-life wastes and chars produced from bio sources. The first industrial application in EAF steelmaking dates back to 2005 with the injection of coke and rubber mixes in Australia **[3]**. This process technology was brought about by ONE Steel and the research group of the University of New South Wales, Sydney, Australia, headed by Prof. V. Sahajwalla.

MORE was selected as the engineering partner to set up the injection equipment and controls in many projects, both in and outside the group. These projects were essentially based on using rubber obtained by shredding worn tyres. Tyre recycling is a well established practice in many developed countries. Very often, the bulk material, already processed and cleaned from textiles and tyre cord can be sourced in local markets at very convenient prices. Tyre rubber is a mix of polymers with a high content of carbon (> 85%) and a very limited content of ash (<3%). The residual content of hydrocarbons (<8%) enhances the formation of gas bubbles and promotes a quick response in terms of slag volume increase. A comparison of the composition of various carbon alternatives is shown in *Table 4*.

Components	Met Coke	HDPE	Rubber
Carbon %	77.7	85.5	85.48
Hydrogen %	1.11	14.2	6.96
Sulphur %	0.28	0.3	1.68
Nitrogen %	1.21	-	0.25
Heat Value MJ/kg	30	46.5	40.16

Table 4 **Composition of carbon alternatives [3]**

Shredded rubber tyres therefore a very convenient material to use as a substitute for metallurgical coke. Total substitution does not achieve the best result in operations, because the rate of reaction is too fast and dissipates the benefit of increasing the slag volume too early (*Figure 10*). A blend of 50% rubber and 50% coke is, by experience, the way to achieve the best results in terms of foaming volume and stability. In fact, a proper combination of rubber and anthracite produces a superior foaming slag volume than the anthracite alone thanks to a higher thermal contribution and a greater release of gas volume (*Figure 11*). However, these two factors must be limited, or the greater heat released lowers the viscosity of the slag, turning the slag into a liquid and generating larger bubbles that cause slopping. A conceptual system for materials handling to promote slag foaming is shown in *Figure 12*.

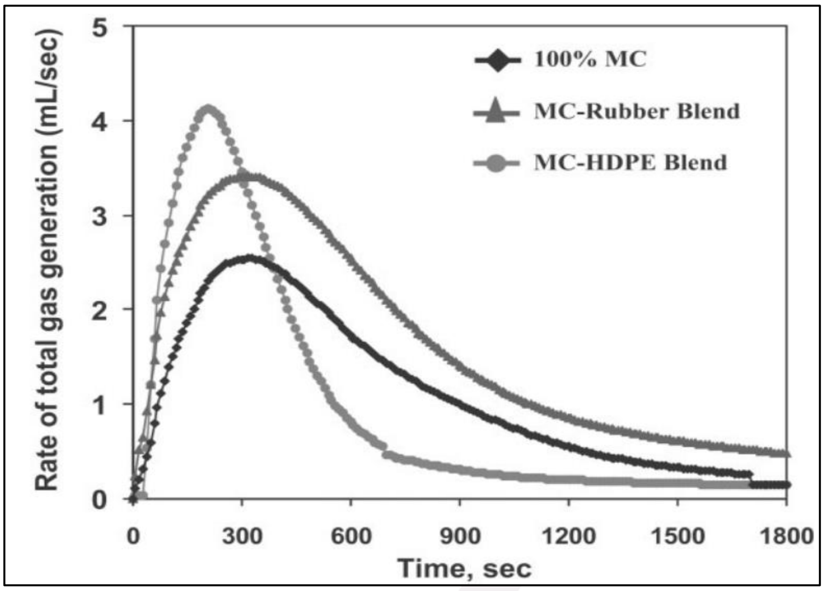

Fig 10 **Kinetics of gas generation of different materials [4]**

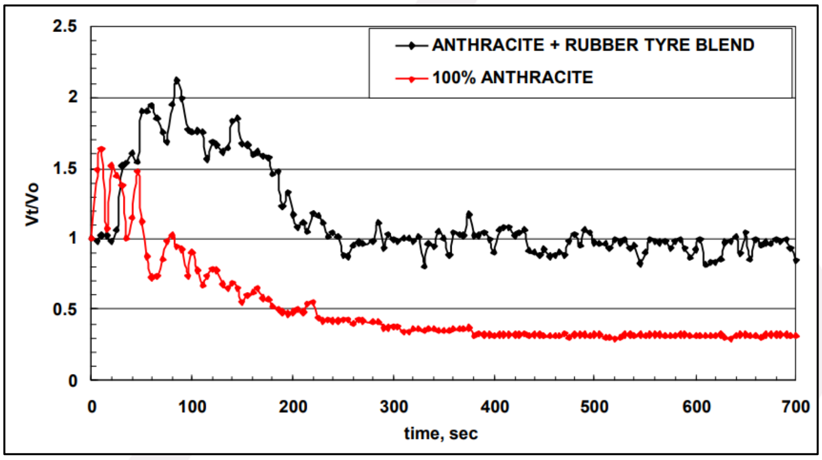

Fig 11 **Slag foaming height comparison over time**

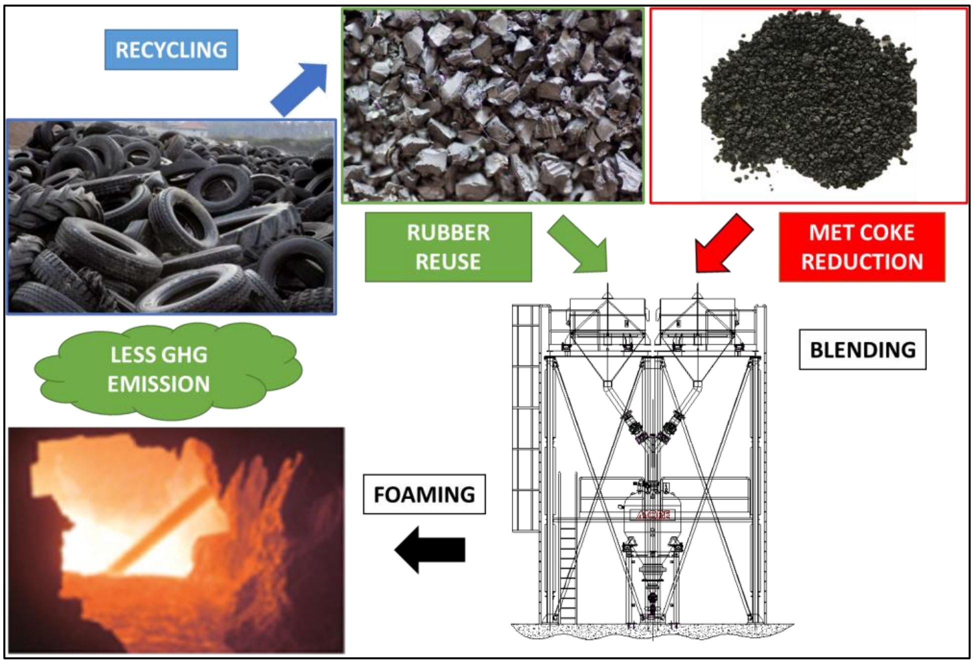

Fig 12 **Conceptual system for materials storage, blending and injection in EAF, to promote slag foaming**

Storage and injection systems must be arranged with maximum flexibility to enable the steelmaker to adopt the proper mix for the furnace process, adapting to variations in the quality of available materials. For this purpose, MORE has developed a specific technology for polymer injection, with the capacity to prepare any blend of coke and alternative material. The required mix is prepared in pressurised vessels, drawing exact quantities from each storage silo at a proper flow rate, such that it is ready to be delivered to the EAF at precise feed rates (*Figure 13*).

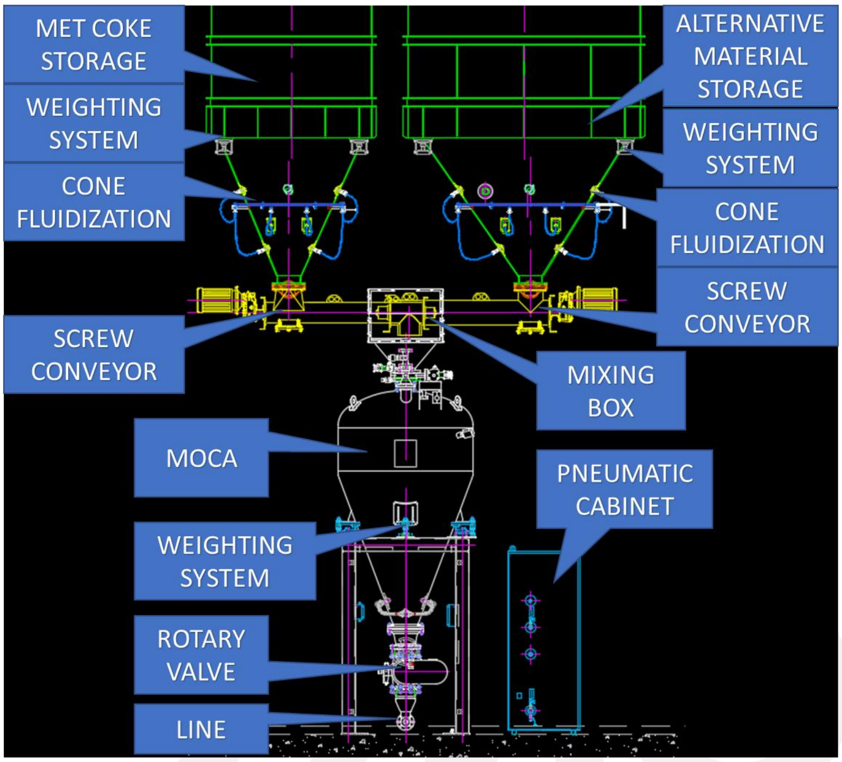

Fig 13 **MORE solution for polymer injection technology**

In 2021, MORE received an order from Tenaris for an EU research project to inject blends of different polymeric materials with met coke at their Electric Arc Furnace at Silcotub in Romania. The alternative materials ranged from raw polymers to recycled plastic waste (*Figure 14*). A range of steelmaking by-products were included in the research, such as white slag and sludges.

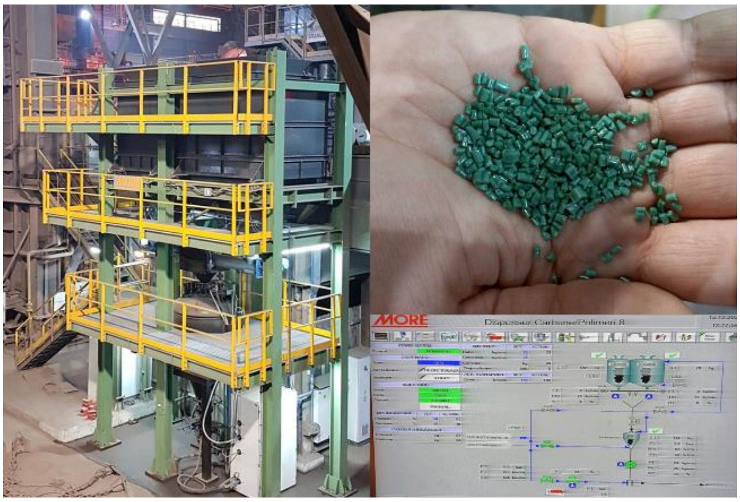

Fig 14 **Integrated plant for polymer and coke mixing and injecting into EAF, Tenaris Silcotub 2021**

Another very promising material for EAF injection is the polymer Bluair® (*Figure 15*). It is produced alongside plastic waste residue in the recycling industry, after all the fractions that can be conveyed to the plastic industry have been removed. This material contains a high fraction of hydrocarbons, the chemical composition intrinsically changes across a wide range and it has a low bulk density of 300kg/m^3. These factors are difficult to manage in EAF production. Alongside the effects on foaming slag, some potential drawbacks are localised refractory wear, an increase in energy consumption and overheating.

Fig 15 **Bluair® flake polymer**

With all the challenges faced in these projects, it can be concluded that there is still a lot of optimisation work to be done. Our vision is for a dosing and injection system that will have the flexibility to compensate for low bulk density and variation in chemical analysis.

CONCLUSIONS

MORE has over 30 years of expertise in developing the chemical energy package for electric arc furnaces and is actively contributing to the green steel transformation. Short term solutions are readily available. The M-ONE injection system enables the efficient use of traditional gaseous fuels, oxygen and slag formers, improving productivity and immediately lowering specific emissions. Full control valve stands accurately regulate technological gases, eliminating all the inefficiencies associated with the unnecessary application of production gases during non-productive time.

The transition to green hydrogen as a substitute for gaseous fossil fuels, such as LPG, LNG and natural gas, will be a long term roadmap in steelmaking. Coke oven gas, a hydrogen rich gas mix, has been widely used for many years as an available by-product of the blast furnace steelmaking route. The availability of green hydrogen as a commodity will take many decades. The current cost of hydrogen as compared with natural gas, which is the primary gas for production, are far from break even, even when emissions trading credits are taken into account.

MORE Research & Development has run specific projects since 2022 in cooperation with university institutions and qualified laboratories, to jointly develop new efficient technologies to use pure hydrogen as a gaseous fuel substitute in steelmaking applications. Carbon injection will remain central to the EAF route for a long time to come, crucial for slag foaming and crude steel refining. MORE is actively promoting the use of carbon-neutral supplies to replace fossil coals and petcoke. Through many projects in the past decade, MORE has developed comprehensive experience in the injection of coal substitutes into the EAF. Among others, the partnership agreement with an Australian steelmaker which holds many patents for the injection of carbon and polymer mixtures, has consolidated very reliable know how in process optimization, equipment sizing and control systems.

Another promising route is the injection of polymers produced from waste recycling. This is a low-cost carbon substitute, dropping the cost of emissions trading and eliminating municipal expenditure on incineration and landfill. Last, but not least, MORE carbon injection technologies have been selected by many customers, especially in the US market, to inject bio-chars.

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