

# Sustainable production of low carbon, renewable fuels by fermenting industrial process gasses from the iron and steel industry

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## Summary

Technological solutions, to utilize process gases from the iron and steel industry for production of fuels and chemicals, are an attractive sustainable and economic approach for industries today. This innovative approach converts carbon and hydrogen-rich off-gases, such as coke oven gas, blast furnace top gas and also converter gas into liquid based energy sources through a biological gas fermentation process to produce preferably ethanol or other chemicals. To produce ethanol, an integrated fermentation system with additional downstream installations is required to treat the fermentation product and waste streams. The treatment of the fermentation waste streams results in a number of by-products, usable for internal or external applications. By returning the by-products to an integrated steel plant or recovering the inherent energy, the fermentation system can be operated in circular system, with minimal waste. The first European commercial scale application of this technology is being developed at the ArcelorMittal steel plant in Ghent with the objective of producing 80 million liters of ethanol per year to be used as renewable transport fuel.

## Key Words

Gas fermentation, ethanol, process gas, carbon emissions, renewable fuel, ecological, environmental

## Introduction

Recycling carbon emissions from iron and steel production units provides an important new source for fuels and chemicals production. Off-gases generated from the steel industry contain significant amounts of carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>) and hydrogen (H<sub>2</sub>). Governments around the world are setting ambitious targets for reduction of stationary carbon emissions from industrial installations such as the steel industry, thereby adding significant costs to steel production. However, a new development in off-gas recycling while improving a steelmaker's economic competitiveness, through promotion of the circular economy.

This paper gives an overview of near-term GHG reduction and economic opportunities arising from fermentation of iron and steel making off-gases and further presents the advantages of the zero waste concept by recycling the produced by-products process internally or within the integrated steel plant by reducing the consumption of external added raw materials.

## Materials and methods

In the steel industry, carbon is used primarily as a chemical reactant to reduce iron oxide to metallic iron. This is an important distinction from the typical industrial use of carbon as a fuel. While alternative energy sources such as wind and solar can replace fossil fuels, they cannot replace carbon in steelmaking. Thus, the resulting steel-mill waste

gases are unavoidable residues of industrial production.

The residual gases produced through this chemical reaction are an inevitable consequence of the chemistry of steel making. The production of coke, with the coke oven process, generates process gas rich in hydrogen (H<sub>2</sub>) and methane (CH<sub>4</sub>). The concentration of carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) is rather low, compared to the off-gas concentration of an iron production process. Off-gases generated with the blast furnace process or with one of the direct reduction processes contain significant amounts of carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), but lower amounts of hydrogen. In an integrated steel plant, these gases are used for thermal applications or for electrical power generation. In some cases, the produced off-gas needs to be flared.

LanzaTech's gas fermentation process is a new approach to reduce CO<sub>2</sub> emissions while producing low carbon liquid fuels and chemicals, which captures and recycles carbon-rich industrial off-gases to the global steel and ferro-alloy industry. The process uses naturally occurring microbes from the family of acetogens, or gas-fermenting organisms. These organisms represent one of the earliest life forms on Earth and utilize gases as the sole source of energy for their entire life cycle. LanzaTech was founded to take advantage of these organisms, to reduce carbon emissions and produce sustainable biofuels and chemicals without impacting land or food resources.

## Process Overview

At its core, LanzaTech's gas fermentation technology uses carbon-containing waste and residue gases as both a nutrient and energy source for proprietary microorganisms rather than sugars as in traditional fermentation. The microbes in turn produce a diverse product suite including low carbon fuels and high value chemicals used in every day applications.

Carbon-rich industrial gases such as off-gases produced during steel manufacture are transformed into commodity fuel and chemical products in a continuous process, providing a novel approach to carbon capture and reuse.

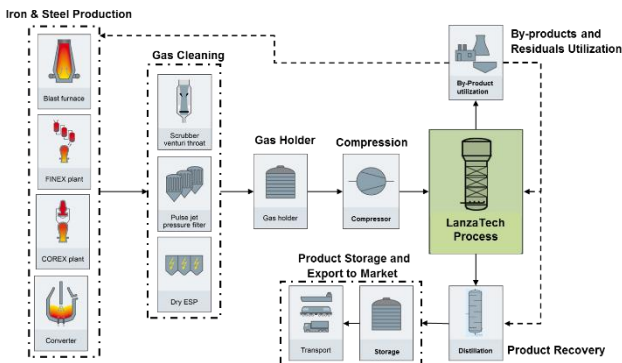


Fig.1 – Overview of the gas fermentation steps

Instead of sending a residual gas stream to a thermal energy or electrical power generation unit, the gas, which is cooled and pretreated (e.g. removal of particulates, hydrocarbons, oxygen and other harmful elements pre-sent in the process gas) by Primetals gas handling technologies, is then injected into a fermentation vessel containing proprietary microbes and liquid media. The microbes convert the CO, CO<sub>2</sub>, and H<sub>2</sub> into ethanol and chemicals that can be recovered from the fermentation broth.

This is similar to the way that yeast makes ethanol from sugars except that the gases provide the sole source of carbon and energy for LanzaTech's process. The fermentation products are separated from the fermentation broth and sold as a fuel grade gasoline blending component or as chemical intermediates.

A unique aspect of the process is the ability to utilize gas streams with a range of CO and H<sub>2</sub> compositions to produce fuels, such as ethanol, and chemicals, such as 2,3-butanediol, at high selectivity and yields. While both CO/CO<sub>2</sub> and H<sub>2</sub> are utilized in the gas fermentation process, LanzaTech's proprietary microbes are also able to consume hydrogen-free CO-only gas streams, due to a highly efficient biological water gas shift reaction that occurs within the microbe. This reaction allows the bacteria to

compensate for any deficiency in H<sub>2</sub> in the input gas stream by catalyzing the release of hydrogen from water using the energy in CO.

The low temperature, low pressure gas fermentation route benefits from tolerance to a wide variety of impurities and pollutants, reducing the need for extensive gas clean-up or conditioning. The microbes used in the gas fermentation process convert carbon gases to ethanol at very high selectivity compared to conventional chemical synthesis routes. The result is a higher overall fuel and thermal efficiency..

## Process Steps

The general process integration scheme for an integrated steel plant is described as follows:

1. A metallurgical process unit such as blast furnace, direct reduction plant, BOF converter or ferro-alloy furnace produces off-gas containing CO, H<sub>2</sub>, CO<sub>2</sub> and other components.
2. The gas is passed through gas clean-up systems to remove particulate matters and eventually hydrocarbons and oxygen. The gas is also cooled to around 40°C. At this stage, steam may also be generated from the sensible heat in the gas using a heat recovery unit, for use in downstream product recovery.
3. Where the gas originates from an intermittent source, such as steel converter trains, it is stored in a gas holder to regulate flow. Where gas is continuously produced, as in most iron making processes, the gas holder is smaller or may not be required.
4. The gas is compressed for injection into the bio-fermenter.
5. The gas is injected into the fermentation reactor, which is filled with an aqueous media (mostly water) and industrial microbes, where it is consumed in a single pass. The microbial biomass continuously excretes chemical metabolites, such as ethanol and 2,3-butanediol (BDO) into the media.
6. Media is continuously bled off and conventional product recovery systems are used to extract products. In the case of ethanol, this is a distillation system, while for chemicals other commercially available technologies are used.
7. Water and media components are treated and recycled to the fermentation or discharged for further use within the integrated iron and steel industry.
8. Sludge and biomass, removed from the system can be used to produce energy in form of biogas.
9. Biogas and tail gas from the fermentation system are used for generation of required thermal energy or is used and blended with other gases to produce electrical energy at the local power plant.
10. Product and by-product is stored in tanks for export, ideally using rail tank cars, as most mills have railhead access for coal and steel shipments. By-

products and residuals are conditioned, if necessary, and prepared for utilization either for the fermentation process itself or for other applications within the integrated iron and steel work.

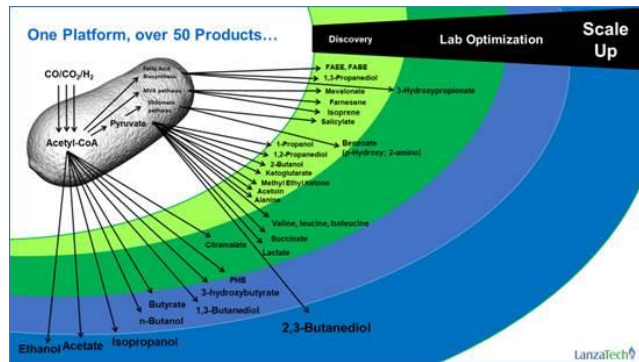


Fig.2 - LanzaTech Gas to Liquid Platform

Figure 2 shows the range of products that can be produced either in commercial scale, in pilot scale or are under development. The business strategy allows a quick switch of final product without major plant modifications.

The current process makes fuel grade ethanol that meets specifications EN15376, D4806 (fuel additive) and D5798 (primary fuel). LanzaTech has also developed a commercial offering for an alcohol to jet technology that enables conversion of low carbon ethanol to sustainable aviation fuel. The technology developed in collaboration with US National lab, PNNL, is now being licensed by LanzaTech.

### Economic Benefits

Revenue derived from the sale of marketable commodities such as fuels, chemicals and by-products far surpasses any other use of carbon-containing gas streams. Multiple techno-economic analyses (TEA) in various regions have determined that gas fermentation typically doubles economic returns from BOF gas utility relative to power production.

Capital costs for a 100,000 tpy ethanol gas fermentation plant based on steel mill off-processing varies based on region. As the technology evolves and based on commercial experience, the LanzaTech gas fermentation process will be able to compete on capex with conventional ethanol production routes. The key point is that steel mill off-gas based ethanol is a more sustainable pathway that does not compete with the food chain or impact land use. Steel mill off-gas based ethanol production is cost competitive on a CCOP basis with incumbent routes.

### ENVIRONMENTAL BENEFITS

The technology also has a significant impact on the carbon footprint of the produced products. Separate lifecycle analyses (LCAs) performed in conjunction with Michigan Technological University, USA and Tsinghua University, China and E4tech in the UK, have shown that producing bioethanol from steel mill off-gas results in a product with lifecycle carbon emissions 50-87% lower than conventional gasoline depending on the carbon intensity of the local electrical grid.

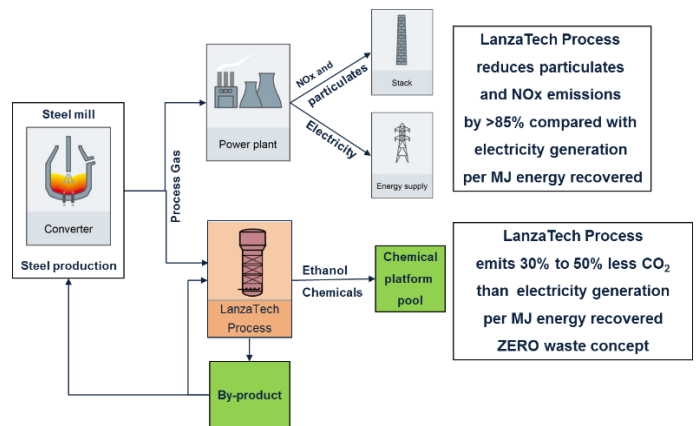


Fig.3 - Emissions Reduction Benefits - Not Just CO<sub>2</sub>

Where off-gases are used as a process input, an added benefit for the host steel mill is a reduction in CO<sub>2</sub> emissions, as some carbon that would normally be combusted in heat and power production, or flared, is instead converted into a liquid product. Globally, up to 150 million tons of CO<sub>2</sub> emissions could potentially be avoided by re-using available steel mill gas residues through the LanzaTech process. Gas fermentation also avoids combustion of the off-gas stream being converted, resulting in a substantial reduction in Particulate Matter (PM), SO<sub>x</sub> and NO<sub>x</sub> emissions up to 85% and higher. All by-products are internally or externally recycled, which leads to reductions of fresh imported raw materials. In the longer term, it can be anticipated commercial production plants to deliver even greater greenhouse gas reductions than those presented here. If or when credits for these reductions are included, the economic value of using this type of technology will be further enhanced.

### Steelmanol

The 80 million liters ethanol per annum Horizon 2020 Steelanol project at ArcelorMittal, sufficient to fuel a million cars with ethanol blended gasoline, will demonstrate the added value of recycling waste streams, not only by reducing emissions at the steel mill source, but by keeping fossil fuels in the ground through the production of commodity chemicals and fuels that would otherwise be made from oil.

To produce the total amount 80 million liter ethanol, a small portion from the produced blast furnace off-gas will be utilized. To test the capability of the ArcelorMittal blast furnace gas with the LanzaTech fermentation process, a gas testing unit was successfully operated at ArcelorMittal in Ghent.

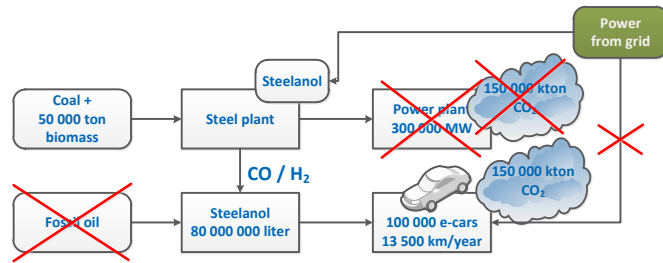


Fig.4 – Impact of Steelanol in CO2 reduction

Approximately 50% of the carbon used in the chemistry of steelmaking leaves the process as carbon monoxide. LanzaTech’s technology, however, recycles the waste gases and ferments them with a proprietary microbe to produce bioethanol. Every ton of bioethanol produced, displaces 880 liter of gasoline as well as reducing CO2 emissions by 2.3 tons. The impact of the Steelanol project is comparable to replacing 100.000 gasoline fueled cars with electric cars.

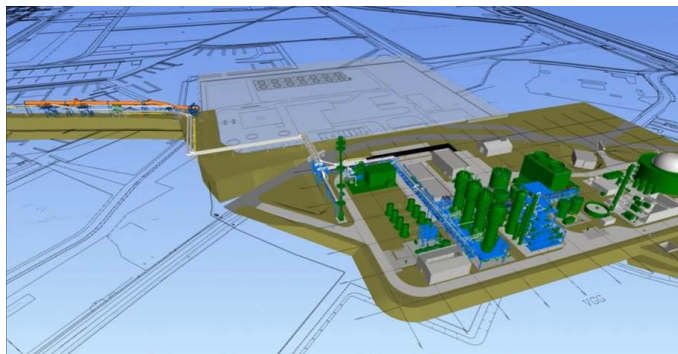


Fig.5 – Design of Steelanol at ArcelorMittal Ghent

A total of €10.2 million has been granted under the EU’s 2020 Horizon program for research and development. The aim is to start up a first large scale reactor the end of 2020 and to run at full capacity in 2021. The design of the Gent Steelanol plant is completed and includes innovative distillation, water treatment and energy efficiency concepts. See Figure 5 for 3D design of the AM Gent plant.

The ethanol produced can also be further processed to produce sustainable aviation fuel via the alcohol to jet(ATJ) pathway that LanzaTech has developed. Sustainable aviation fuel demand is poised to grow and ATJ could play a pivotal role in meeting this demand.

Yet another outlet for sustainably produced ethanol is the chemical industry. The industry is under market pressure to produce lower carbon inputs for the various plants end products. Hence, low carbon ethylene can address part of this growing need.

## Discussion

Many in the iron and steel industry are used to thinking of waste gas streams for productive use, or using the streams for onsite or off-site combined heat and power. It is safe to say, however, that revenue derived from the sale of marketable commodities such as fuels and chemicals far surpasses any other use of carbon-containing gas streams.

For ethanol alone, the market opportunity represented in the emissions of the steel industry is very significant. An analysis of large steel plants around the world reveals the potential to produce more than 40 billion liters of ethanol per year in China alone. Europe’s steel industry could produce almost twenty billion liters. The United States could see almost four billion. In addition the ethanol can be converted to jet fuel (2 liters of ethanol for 1 liter of jet fuel) to be used in aviation transport, where in the near future no sustainable alternative is available that is economically viable. Also in heavy fuel transport, ethanol is the best candidate for a sustainable fuel. Next to the transport sector the fermentation technology can be used to produce basic chemicals such as ethylene and propylene, which are used in the manufacture of everyday consumer goods. This represents a perfect example of the circular economy in which the carbon is recycled and locked into a new product, which can be further recycled, closing the loop from waste gas to chemical feedstock to consumer good that can be recycled further.

Utilization of process gas from Iron and Steel plants to produce ethanol, chemicals and by-products, results in sustainable, economic and ecological benefits for both producer and consumer. Growing energy demand and the increasing importance of alternative fuels requires new sources and possibilities to assure the supply of required energy in the future. The USA, Europe, South America and ASEAN are already the top producing regions for sustainable chemicals and a growing biofuels market force, as a result of abundant natural feedstock resources, government industrial policy and innovative national oil companies. Combining the region’s steel industry with gas fermentation enables profitable green growth for both the steel and chemicals industries

## Conclusion

Gas fermentation offers a new route to create value from iron and steelmaking off-gases while also meeting requirements to reduce greenhouse gas

emissions. Additionally, the flexibility of gas fermentation will enable production of a wider range of chemicals over time, creating additional value for the iron and steel industry and deepening connections with the chemicals industry.

The unique advantage of gas fermentation technology to decouple emissions reduction and compliance costs by diverting carbon into valuable products introduces a process to address waste gases that pays for itself.

This innovative technology promotes a global circular economy, recycling waste carbon from steel mill off gases to directly produce ethanol, higher alcohols and other commodity chemicals, and via further thermo-chemical conversion, hydrocarbon fuels, such as jet fuel. LanzaTech's Carbon-Recycling Process creates an opportunity for the steel industry to become a significant contributor to the fuel and chemicals value chains while substantially enhancing environmental performance.

Gas fermentation opens up a long-term vision of integrated steel and chemical complexes, where all gas streams can be efficiently utilized to create products and maximize value. This will create a relationship between the steel and chemicals industries similar to that between oil refining and chemicals today, where steelmakers are an upstream feedstock and utilities suppliers to chemical manufacturers

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