



White Paper

Steel2Chemicals: Advancing Circular Carbon in the Industry

This White Paper focuses on a four-year pilot project called Steel to Chemicals (S2C) that aims to address the significant greenhouse gas emissions resulting from the production of steel, chemicals, and plastics. The project demonstrates the feasibility of utilizing gases from steel manufacturing as feedstock for the chemical industry, offering mutual climate benefits by reducing emissions for both sectors. The White Paper presents the key findings from the pilot project and discusses alternative approaches for reducing emissions in the steel and chemical industries.

Colophon

Title

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Steel2Chemicals project

The **Steel2Chemicals** project focuses on the development of a closed value chain in which CO from residual gases from steel production is used as raw material in the chemical industry.

www.ispt.eu/projects/steel2chemicals/

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Consortium partners

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Foreword

Linking the carbon chains in industry

The pioneering Steel2Chemicals project is a perfect mirror of what industry must achieve in the coming era. Collaboration between different sectors and knowledge institutes is required, in search of innovative carbon pathways, through ingenuity and conviction. Connecting the steel and chemical industries, Steel2Chemicals investigates the feasibility of a 'second life' for carbon from steel mill gas. Projects like this are essential for creating a sustainable industry.

The scale of steel gas and the ever-growing demand for carbon feedstock in the chemical industry, particularly in plastics manufacturing, are a good match. Both sectors also share a common objective. The steel industry, one of the largest industrial emitters of the greenhouse gas carbon dioxide, is facing the challenge of drastically reducing its fossil carbon footprint. Meanwhile, the chemical industry is searching for sustainable alternatives to its traditional fossil carbon sources. Steel2Chemicals bridges these two sectors. This project also represents a paradigm shift, where the carbon emissions of one industry become resources of another.

Regardless of the actual outcomes, the S2C pilot project is exemplary for taking a step forward on the long pathway of research, development, and deployment of new technologies. Following earlier research in lab tests and desktop analysis, the prospects of this type of Carbon Capture and Utilization (CCU) are good. But these promises have yet to be demonstrated in practice, in a scaled pilot. This requires collaboration, a collective effort of visionaries and commitment from both the steel and chemical industries.

Expectations were high. For many, the Steel2Chemicals project may not have fulfilled all promises. For me, the results of this pilot do not come as a surprise. It is well known that innovations face major challenges as soon as they are reaching the pilot, demonstration or even the market phase. That's what pilots are for!

The value of this pilot should not be underestimated. After more than four years of pilot research and analysis, we know a lot more about the CCU's prospects than we did before. Yes, the S2C process may become a feasible CCU option in large parts of the world, because blast furnace steel mills are still large business as usual, and producers of valuable carbons. Concerning industries in the EU, the results of this pilot lead us to options that are beneficial for business and climate and that yet must be further explored. In this way, the pilot findings are a prerequisite for the industry boards to make well-informed decisions about the low-fossil-carbon-future of their companies.



Kees Biesheuvel
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ISPT Program Director Circular Carbon

Advancing Circular Carbon in the Industry

In short

- The Steel2Chemicals (S2C) pilot project aims to reduce greenhouse gas emissions by interconnecting the steel and chemical industries, using gases from steel manufacturing as feedstock for chemical production.
- The project successfully demonstrated the viability of this interconnection, showcasing its potential for cost-effective emission reduction compared to alternative methods.
- Implementing large-scale S2C installations faces challenges due to specific process technology knowledge, significant investments, and space limitations at steel mill sites.
- Alternative approaches such as CCS, hydrogen-based steel production, and utilizing biomass or recycled plastics as feedstock also offer potential for reducing emissions in the industry.

The production of steel, chemicals, and plastics heavily relies on fossil fuels as an energy input and raw material. However, this dependency results into significant greenhouse gas emissions unless we find ways to either prevent emissions or avoid the use of fossil fuels altogether. Addressing these objectives is the central focus of the ambitious four-year pilot project called 'Steel to Chemicals' (S2C).

This pilot project demonstrates the feasibility of utilizing gases from steel manufacturing as feedstock for the chemical industry. This interconnection holds great promise due to its potential for mutual climate benefits. By valorizing the steel mill off-gases as a feedstock for chemicals, the steel industry can reduce its greenhouse gas emissions. Simultaneously, the chemical industry can replace a portion of its fossil feedstock with these "second-hand" carbons, resulting in reduced greenhouse gas emissions. The Steel2Chemicals project is a collaborative effort among steel manufacturers, the chemical industry, and knowledge institutes.

This White Paper presents the key findings of the pilot project from various perspectives. Firstly, the pilot factory successfully demonstrated the viability of this interconnection. Additionally, it was shown that the costs of implementing this project are lower than the alternative of doing nothing and having to pay for EU emission allowances.

However, achieving this positive outcome does not necessarily mean that numerous S2C factories will be established worldwide. Building and operating such a plant at a steel mill site requires specific process technology knowledge, significant investment, and ample space. Moreover, political and economic circumstances in the EU are not particularly favourable for this option. Practical experiences and modelling indicate that, apart from opportunities in conventional steel manufacturing outside the EU, other processes are more promising for drastically reducing emissions in the steel industry or reducing the use of fossil carbon in the chemical industry. Nonetheless, the S2C pilot has uncovered interesting findings that can contribute to exploring alternative approaches.

The Industry’s Perspective

In the EU and elsewhere, fossil-intensive steel manufacturing and the chemical industry face significant challenges in terms of their greenhouse gas balances and use of fossil carbon resources. The EU is currently aiming for a zero-emission industry within the next twenty years, with the intention of ceasing the issuance of new emission allowances by 2040. As industries strive towards this zero-level, the costs of allowances are expected to rise, making business cases for alternative low-fossil carbon technologies more viable.

Industries are increasingly exploring their best options. Should they focus on reducing energy and fossil fuel usage? Should they prioritize green electrification or green hydrogen? Alternatively, should they consider capturing and storing carbon emissions underground (CCS), or utilization of these gases (CCU)? Among these options, capturing and incorporating carbon into products presents an interesting alternative, as long as the products themselves are durable or part of a circular economy. Carbon Capture and Utilization (CCU) is the primary focus of the S2C project.

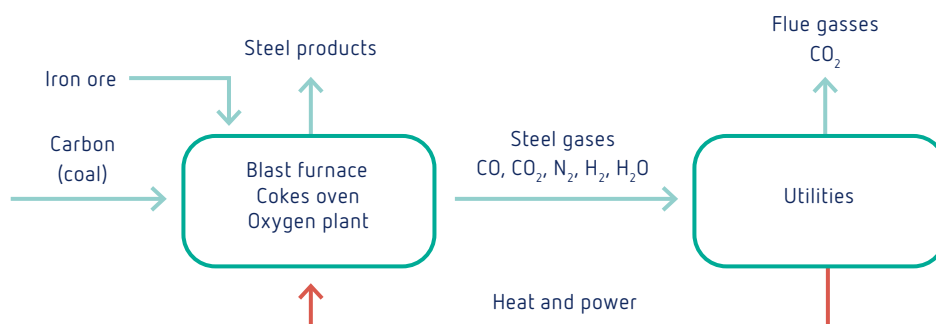
The Pilot Project

The S2C pilot project involved the collaboration of steel mills such as ArcelorMittal in Belgium¹, along with the chemical industry represented by Dow Terneuzen in the Netherlands. Knowledge institutes including TNO (NL), Ghent University (B) participated, as well as the Institute for Sustainable Process Technology (NL). This diverse consortium exemplifies the nature of industrial synergies—cross-border and cross-sectoral collaboration with different interests, but with common goal of reducing their climate impact.

The Primary Carbon Pathways in Steel and Chemicals

The S2C process essentially connects the carbon pathways of two fossil-intensive industries. How does it work?

Steel



Basic carbon pathway in steel manufacturing

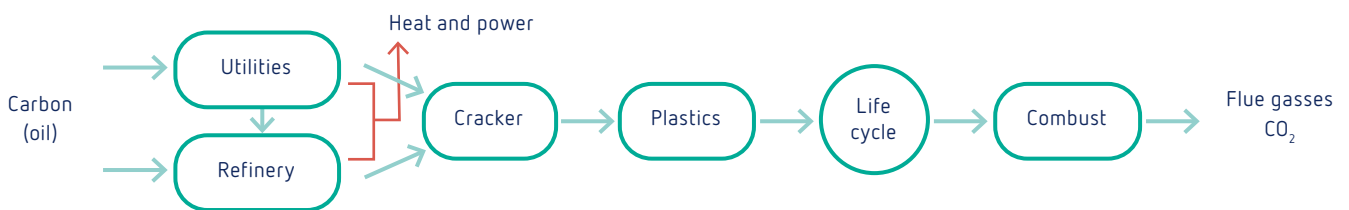
¹ Originally, the pilot was to be commissioned at the Tata Steel Nederland (TSN) site in IJmuiden. However, over the course of the project TSN changed the scope of their sustainability agenda but remained present as a partner.

Conventional steel manufacturing employs fossil carbon for two primary purposes. Firstly, it serves as the energy source for the heat required to melt iron ore and intermediate products during the steel-making process. Secondly, carbon is necessary for the chemical reduction of iron ore. In this process, carbon molecules facilitate the removal of oxygen from iron-oxides through a heated chemical reaction in the so-called 'blast furnace'. Additionally, a small amount of carbon is required to impart strength to the steel. Carbon, in the form of cokes derived from coal in cokes ovens adjacent to the blast furnace, is used to fulfil these purposes.

These combined processes yield steel and a mixture of carbon-rich gases known as steel gas. Steel gas is composed of carbon monoxide (CO), carbon dioxide (CO₂), hydrogen (H₂), water (H₂O), nitrogen (N₂), and various impurities originating from both iron ore and coal.

The carbon fraction of steel gas is of particular interest when considering its climate impact. By default, this steel gas is utilized for power generation, resulting in additional CO₂ emissions. However, by employing CCS technologies, the CO₂ emissions can be mitigated. Alternatively, if the carbon in steel gas is reused, such as by the chemical industry in the production of plastics, the emissions from the entire system can be roughly halved. Reductions can even be bigger if the carbon products will be re-used a couple of times, or if resulting CO₂ emissions are captured and stored.

Chemicals

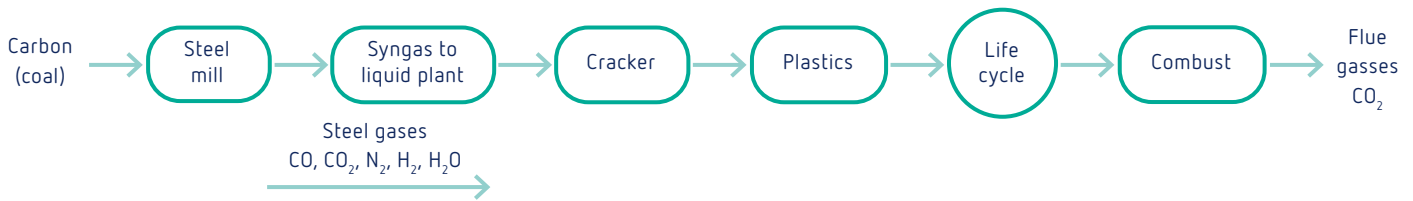


Basic carbon pathway in chemicals

The chemical industry also utilizes fossil hydrocarbons, such as oil or natural gas, for the same dual purpose as steel. Typically, the majority of fossil hydrocarbons, which primarily consist of large molecules, are "cracked" into a mixture of smaller molecules to prepare them for use in the production of plastics. A smaller portion of hydrocarbons is employed for energy generation.

The climate impact of all carbon throughout its life cycle is significant. Combustion of carbon directly contributes to greenhouse gas emissions, unless CCS is implemented. Additionally, the fate of carbon that ends up in products is crucial since, at the end of their life cycle, such as in plastics or other chemical products, they also will be combusted. However, by plastics recycling or implementing circularity in plastic products themselves, the impact can be minimized.

The Pilot: Shortcutting Steel Gas Carbons to Chemical Feedstock



Basic carbon pathway in Steel2Chemicals

The S2C pilot project explores a new carbon value chain between the steel and chemical industries. If proven valuable, this interconnection would involve significant volumes of carbon-rich steel gas that closely match the feedstock requirements of a large chemical factory.

In essence, S2C converts the carbon in steel gas into liquid hydrocarbons, known as naphtha, which can then be fed into a 'cracker' to produce smaller molecules for chemical production processes. To achieve this, the S2C process removes carbon atoms from the steel gas. The addition of hydrogen (H_2) facilitates the production of a mixture of hydrocarbons ($CxHy$), specifically the naphtha intermediate feedstock for plastic production.

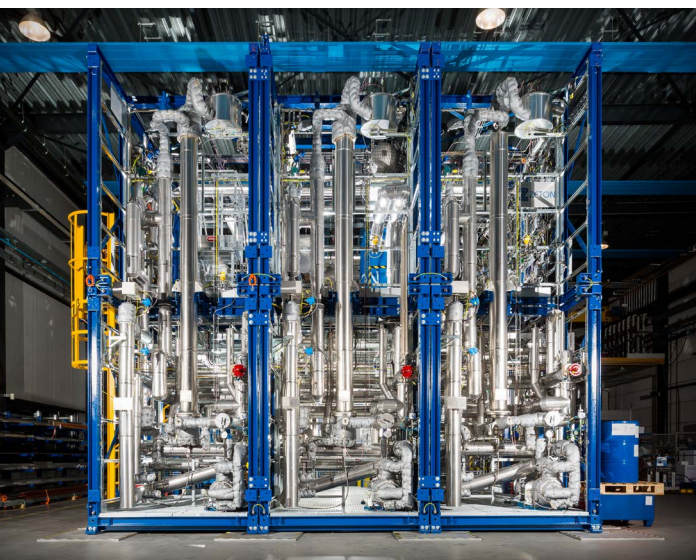
The process of converting steel gas to naphtha was already successfully tested under laboratory conditions. It is based on the Fischer-Tropsch (FT) process, a widely acknowledged process technology that is a hundred years old and used for producing naphtha from various carbon sources such as natural gas, coal, and biomass.

In the FT process itself, a series of chemical reactions convert the carbon in the steel gas, along with added hydrogen (H_2), into a range of hydrocarbon molecules. These chemical reactions are driven by heat and facilitated by a novel catalyst from Dow, which causes the carbon and oxygen atoms to separate and the carbon and hydrogen atoms to recombine.

In practical terms, the carbon in the steel gas mixture exists in the form of carbon monoxide (CO) and carbon dioxide (CO_2). CO is the desired component as CO_2 is unreactive and requires a significant amount of energy to split. The efficiency of the FT process will improve if the steel gas fed into the reactor has a high CO content. This necessitates a purification step to remove nitrogen (which constitutes more

than half of the steel gas content), carbon dioxide, and other contaminants. The efficiency of the overall S2C performance heavily depends on this purification process.

The pilot plant, constructed next to the ArcelorMittal steel mill, operated for nearly two years. A previous pilot project called C2V (Carbon to Value) laid the groundwork for the removal of CO_2 , which can be sequestered (CCS). The S2C pilot plant was supplied with both clean and bottled CO, H_2 , and N_2 , as well as realistic steel gas from the neighbouring blast furnace. The steel gas used in the plant did not contain gases originating from the cokes



oven due to the dominant contaminants present there. Regardless of the source, the steel gas contained over 50% nitrogen. Throughout this period, the pilot plant provided data on performance, conversion rates, operating conditions, mass and energy flows, catalyst stability and regeneration, and various other aspects of the installation. The resulting naphtha product was analysed in a cracker by the University of Ghent to determine its suitability as a feedstock.

Main findings of the pilot

The operation of the pilot plant indicates that the principal processes do work as expected, and the individual steps are interconnected. The input steel gases are successfully converted into naphtha, which meets the required specifications as an intermediate feedstock for chemical production. This confirmation on a larger scale aligns with previous laboratory tests.

However, the pilot plant also revealed several new process technology challenges. While the overall efficiencies of the plant are sufficient, they are lower than expected based on earlier benchmark experiments. The actual steel gas poses more difficulties, especially because the input is not stable.

The C2V process proves effective in removing CO₂ and other contaminants from the steel gas. However, the substantial amount of nitrogen cannot be easily eliminated. Nitrogen is largely unaffected during the conversion process and acts as a 'dead weight' in the Fischer-Tropsch process. It affects the energy and mass balance and reduces the effectiveness of the catalyst. The high concentration of N₂ also results in larger installation dimensions.

Separating CO from nitrogen presents a challenge. Within the project, a promising new separation method was investigated, which may result in a new patent by TNO. However, this method, based on chemical adsorption of N₂ to a specific molecule, is not yet ready for large-scale demonstration.

Analysis: The S2C Case Versus Alternatives

In general, a pilot project is a crucial step towards potential market application. Practical experiences provide better understanding of the process essentials, economics, opportunities, problems, and potential solutions.

One important aspect of the S2C project was obtaining additional input from the pilot to further model the process compared to alternatives. Ghent University conducted part of the analysis on S2C and alternatives using their own models, while ISPT performed the analysis using transition models from the company QuoMare. The analysis compared alternatives, selected optimizations, and analysed overall carbon abatement.

Main Findings of the Analysis

The modelling analysis demonstrates that S2C is a cost-intensive process technology that requires significant investments for large-scale installations. Specifically, the costs associated with separating the nitrogen are not offset by the gains in efficiency. Moreover, the input of H₂ incurs substantial expenses, even if the (grey) H₂ is harvested from natural gas. However, the overall costs per tonne of avoided CO₂ are expected to be lower than the costs of an EU allowance for emitting the same tonne into the atmosphere. Therefore, the interest in S2C is justified, particularly for blast furnace steel mills.

However, from the perspective of both the steel industry and the chemical industry, alternatives exist. Several technologies are available to the steel industry to reduce carbon emissions. Starting from the conventional cokes ovens and blast furnaces, which are still the dominant methods of steel production worldwide, a straightforward option would be capturing the CO₂ at the end of the entire process cycle, after energy production, and sequestering it underground (CCS).

Similarly, other technologies for treating steel gas are available. In the analysis, the route to produce ethanol (using bacteria and additional hydrogen) appears to be more beneficial than S2C, especially because untreated gases can be used as an input in this case. Methanol production or TNO's SEWGS technology (Sorption Enhanced Water Gas Shift) are other alternatives. These alternatives are under development and still face several challenges.

Moreover, alternative methods to convert iron ore into steel are being explored. These newly developed steel processes utilize hydrogen or even electrons to remove oxygen atoms from iron oxide. In all these alternative cases, the S2C technology is only applicable if carbon-rich off-gases become available.

For the chemical industry, as alternatives to fossil carbon feedstock, there are options beyond steel gas, such as hydrocarbons derived from gasified biomass or old plastics. Essentially, the S2C processes can still be applicable here since the carbon specifications in the syngas from these sources resemble those of steel gas—except for the significant amounts of nitrogen. However, the availability of the feedstock remains questionable. Nevertheless, the chemical industry appears to offer the best prospects for a realistic follow-up to the S2C pilot project.

This pilot is developed for the utilization of CO from steel mill waste streams to produce valuable synthetic naphtha as a circular feedstock for the chemical industry.

The unit was designed by Dow and Zeton and built by Zeton for operation at the steel mills of ArcelorMittal in Gent and Tata Steel in IJmuiden and is a key-asset for the Steel2Chemicals project.

 Institute for Sustainable Process Technology

This project is co-financed by TKI-Energie from the allowance for Topconsortia for Knowledge and Innovation (TKI's) of the Ministry of Economic Affairs and Climate

Find out more about
Steel2Chemicals



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