Steel2Chemicals

Final report

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Dow Benelux

ArcelorMittal Gent

Tata Steel IJmuiden

TNO

Ghent University

Institute for Sustainable Process Technology

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(public summary)

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Secretary (penvoerder)	ISPT
Name Program Director	Kees Biesheuvel
Name project leader	Harry van Dijk
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This report describes the process and main outcomes of the Steel2Chemicals (S2C) project which was initiated and executed by a consortium of Dow, ArcelorMittal (AM), Tata Steel (TS), TNO, Ghent University (UGhent) and ISPT. It was made possible by the contribution of TKI Energy and Industry from the PPS toeslag budget.

KPI	Omschrijving
1. Organisatie/ Penvoerder	Stichting ISPT
2. Projectnummer- of dossiernummer	SI-50-02
3. Projecttitel evt. acronym	Steel2Chemicals, S2C
4. TRL bij afsluiting, Hoofdcategorie	Industrieel onderzoek
5. TRL bij afsluiting, Detailcategorie	6
6. Projectsucces	2. Het project is naar tevredenheid afgerond, maar de inhoud van de mijlpalen is gewijzigd;
7. Vervolg	Nader te bepalen, mogelijk verder onderzoek op TRL7 niveau
8. Aantal gerealiseerde peer-reviewed publicaties	0
9. Aantal verwachte peer-reviewed publicaties	Mogelijk 1
10. Aantal gerealiseerde niet-peer-reviewed publicaties	10
11. Aantal aangevraagde patenten	1
12. Aantal verleende licenties	0
13. Aantal prototypes	2 (UGhent pilot plant nafta testfaciliteit, TNO CO/N2 sep. pilot plant)
14. Aantal demonstrators	Dow FT-chemie pilot plant
15. Aantal spin-offs/ spin-outs	0
16. Aantal nieuwe of verbeterde producten/ processen/ diensten geïntroduceerd	1 demonstrator plant van TRL4 naar TRL6
17. Impact	Over het algemeen kan worden geconcludeerd dat het S2C-project de deelnemende partijen in staat heeft gesteld een beter geïnformeerde beslissing te nemen over toepassing van de S2C-technologie, in vergelijking met andere opties. Een eventuele follow-up in een andere toepassing of zelfs een demonstratiefase behoort tot de mogelijkheden.

PUBLIC Summary

Steel2Chemicals: Advancing Circular Carbon 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 Belgium (initially also Tata Steel in the Netherlands collaborated), 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

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 (CO_2), hydrogen (H_2), water (H_2O), nitrogen (N_2), 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

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

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 (H2) 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 CO2 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 CO_2 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 N_2 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 N_2 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 H_2 incurs substantial expenses, even if the (grey) H_2 is harvested from natural gas. However, the overall costs per tonne of avoided CO_2 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 CO_2 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.

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