

STEPWISE Project: Sorption-Enhanced Water-Gas Shift Technology to Reduce Carbon Footprint in the Iron and Steel Industry

An introduction to the project, its aims and its technology

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Industrial processes contribute significantly to global carbon dioxide emissions, with iron and steel manufacturing alone responsible for 6% of the total figure. The STEPWISE project, funded through the European Horizon 2020 (H2020) Low Carbon Energy (LCE) programme under grant agreement number 640769, is looking at reducing CO₂ emissions in the iron and steel making industries. At the heart of this project is the ECN technology called sorption-enhanced water-gas shift (SEWGS), which is a solid sorption technology for CO₂ capture from fuel gases such as blast furnace gas (BFG). This technology combines water-gas shift (WGS) in the WGS section with CO₂/H₂ separation steps in the SEWGS section. Scaling up of the SEWGS technology for CO₂ capture from BFG and demonstrating it in an industrially relevant environment are the key objectives of the STEPWISE project, which are achieved by international collaboration between the project partners towards design, construction and operation of a pilot plant at Swerea Mefos, Luleå, Sweden, next to the SSAB steel manufacturing site.

1. Introduction

Industrial processes contribute significantly to global CO₂ emissions. As an example, the current iron and steel manufacturing process, being very energy and carbon intensive (on average 2.3 t_{CO₂} t_{crude steel}⁻¹), is responsible alone for an annual output of ~2.5–3.0 Gt_{CO₂} yr⁻¹ (1). This represents 6% of total global CO₂ emissions and 16% of total industrial CO₂ emissions. With the Paris Accord and near-global consensus on the need for action on emissions, it is imperative that each industrial sector looks into the development of solutions towards improving energy efficiency and decreasing CO₂ output. To reduce the carbon footprint during steel production, steel manufacturing companies are exploring different technological options, such as using hydrogen instead of coal for iron ore reduction, electrolysis of iron ore, replacing coal by bio-coal (for example residual products from forestry operations), carbon capture and storage (CCS) as well as carbon capture and utilisation (CCU) technologies (2). Among different options for decreasing CO₂ emissions, CCS and CCU technologies have the advantage because they do not require modification of the current steel production process. In addition, captured CO₂ and H₂ can be further utilised to produce high value chemical products, such as 'green' methanol, dimethyl ether, ammonia and contribute to revenue

generation (2). Therefore, the interest of steel making companies in CCS and CCU technologies has been growing significantly in recent years and is a topic of many research programmes and projects.

The STEPWISE project, funded through the European H2020 LCE programme (2015–2019, budget €13M), is looking at reducing CO₂ emissions in the iron and steel making industries. This project aims to decrease CO₂ emissions in the steel making process from about 2 t_{CO₂} t_{steel}⁻¹ to below 0.5 t_{CO₂} t_{steel}⁻¹ by means of CO₂ removal from BFG, a byproduct gas that is generated during steel production. Currently, BFG is utilised for boilers in power plants to produce electricity or it is flared without generating heat or electricity. A significant amount of CO₂ is emitted during these processes. For decarbonisation of the BFG stream, the STEPWISE project proposes to use an innovative approach based on the SEWGS technology, which is a solid sorption technology for CO₂ capture from fuel gases. A combination of bulk conversion of CO in the WGS unit followed by CO₂/H₂ separation in the SEWGS unit enables generation of a high purity CO₂-rich stream intended for storage or further utilisation (such as for production of chemicals) and a H₂-rich stream intended for electricity production (Figure 1) (3–6).

The key objectives of the STEPWISE project are to scale up the SEWGS technology for CO₂ capture

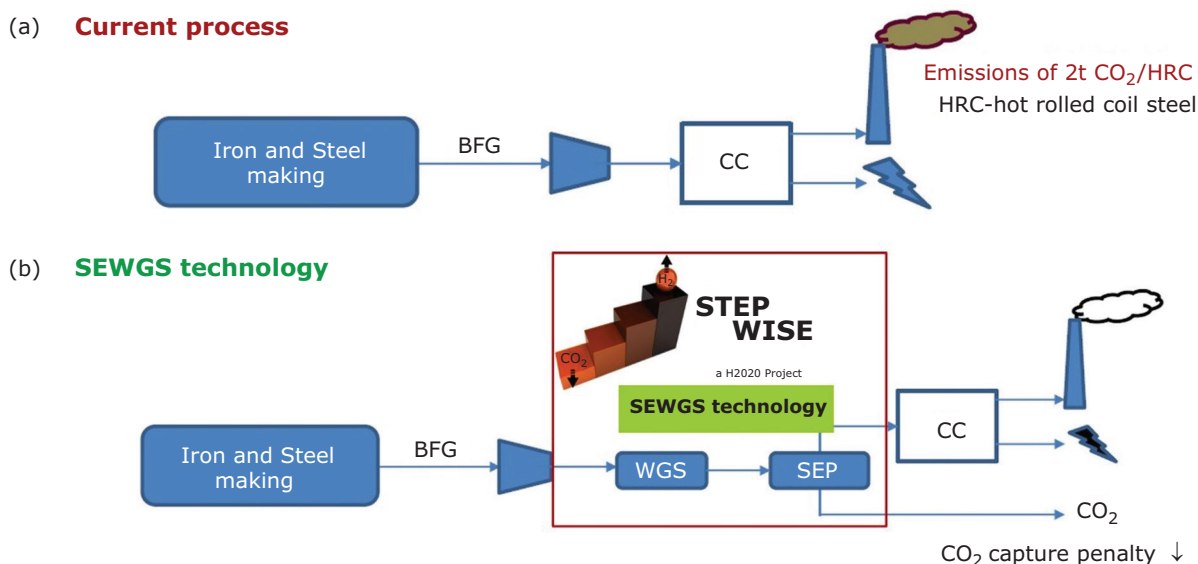


Fig. 1. Schematic representation of BFG treatment in the iron and steel making process: (a) current process; (b) the SEWGS concept (combined cycle (CC), water-gas shift (WGS), separation (SEP), hot rolled coil (HRC) steel)

from BFG, to demonstrate its feasibility in an industrially relevant environment and to bring the technology to Technology Readiness Level 6 (TRL 6). Compared to state-of-the-art CCS technologies, the STEPWISE project aims at:

- higher carbon capture rate (lower carbon intensity, 85% reduction)
- higher energy efficiency (lower energy consumption for capture, 60% reduction)
- better economy (lower cost of CO₂ avoided, 25% reduction).

In addition to reducing the contribution of the steel industry to global CO₂ emissions, SEWGS can potentially lead to cost and energy savings and create new job opportunities in the highly competitive European steel sector.

2. The SEWGS Technological Approach

SEWGS is a solid sorption technology for CO₂ capture from fuel gases such as BFG. It combines water-gas shift in the WGS section with CO₂ adsorption and separation steps in the SEWGS section using a selective solid adsorbent material (3–6). The SEWGS CCS technology has an advantage over conventional wet scrubbing technologies adopted for pre-combustion CO₂ capture, which require at least two water-gas shift reactors (high temperature water-gas shift and low temperature water-gas shift) with inter-stage cooling to achieve a high conversion of CO to CO₂ (Figure 2(a)) (7). Furthermore, downstream of the WGS section, further cooling is necessary to enable the capture of CO₂ by absorption with a solvent. For a power application, the H₂-rich gas again requires heating prior to feeding into a combined cycle. When using the SEWGS process

(Figure 2(b)), both the second WGS reactor and the H₂/CO₂ separation unit are replaced. In the SEWGS technology, the WGS unit, operating at a low steam:CO ratio, takes care of the bulk CO conversion, while CO conversion is completed in the SEWGS unit, and a hot, high-pressure, H₂-rich product stream is directly produced. The sorbent used in the SEWGS unit is WGS active; therefore, the reaction is combined with the *in situ* removal of CO₂, allowing the equilibrium reaction to proceed towards completion without the need for a second WGS reactor. The H₂-rich product at 400°C can be fed to a gas turbine or used in other applications at the steel mill (7).

In the SEWGS technology, a Johnson Matthey WGS catalyst is responsible for the bulk CO conversion in the WGS reactor and reduces CO concentration from ~20% to ~5% (in the dry gas, the average dry gas composition is 19% CO, 25% CO₂, 3% H₂, 15–20 ppm H₂S + COS and 53% N₂). The WGS reaction is an important aspect of the technology as it allows WGS conversion to vary before entry into the SEWGS unit. Since steam is required for the WGS reaction and steam addition directly contributes to efficiency losses in the subsequent power plant, the flexibility of WGS-SEWGS allows overall steam consumption to be minimised (8). In the SEWGS unit, a catalytically active potassium-promoted hydrotalcite-based sorbent (Kisuma Chemicals BV, The Netherlands) completes the CO conversion and separates H₂ from CO₂ (9, 10). This sorbent material is chemically very robust, active for the WGS reaction and able to co-capture other acid gas components apart from CO₂ such as hydrogen sulfide or carbonyl sulfide (6). Moreover, any COS will be converted into H₂S.

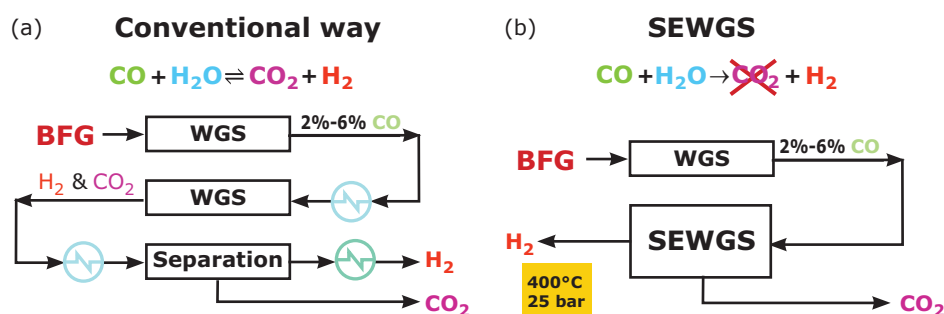


Fig. 2. (a) Conventional layout of a shift section and H₂/CO₂ separation for high-pressure CO₂ capture; and (b) layout for improved CO conversion and CO₂ capture section using the SEWGS technology

The implementation of the SEWGS technology to TRL 6 is addressed as follows:

- The main component reactors are tested in a complete process with performance testing and sensitivity analysis
- The main components are integrated with respect to gas processing
- The sorbent will prove its capacity and mechanical integrity in a real blast furnace environment
- First engineering design of a full scale SEWGS unit (1500 t_{CO₂} day⁻¹) will take place
- Techno-economic assessments will result in investment cost estimation (\pm 30%) and CO₂ avoidance cost (\pm 10%).

In addition to this, the project will provide insight into:

- Validation of the applicability of the SEWGS modelling tool for SEWGS cycle optimisation
- Long-term behaviour (mechanical and chemical) of sorbent with real BFG
- Steam use with real BFG
- Conventional WGS catalyst performance with BFG
- Alternative WGS catalyst performance with BFG including low steam
- Contaminant uptake by the sorbent and the catalyst
- High temperature valve reliability
- SEWGS vessel design and costs
- Impact of CO₂ capture cost on steel production cost.

3. The STEPWISE Consortium

The STEPWISE project involves technology providers, adsorbent and catalyst manufacturers, system design and engineering companies, and industrial end users from the European steel sector. There are nine partners from five European member states (Figure 3). In this consortium,

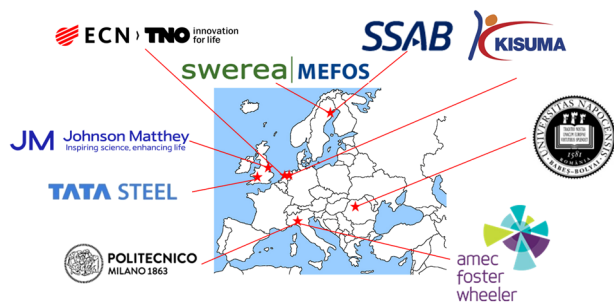


Fig. 3. The STEPWISE project consortium members

the technology providers ECN part of TNO, The Netherlands, and Swerea Mefos, Sweden, lead the pilot plant design, construction, commissioning and operation. A sorbent manufacturer, Kisuma Chemicals, The Netherlands, and a catalyst manufacturer, Johnson Matthey, UK, carry out the development, testing, scale-up and production of sorbent and catalyst materials, respectively. To find out how the SEWGS technology performs against alternative CO₂ capture technologies on technical, economic and environmental levels, research institutes at Politecnico de Milano, Italy, and Universitatea Babeş-Bolyai, Cluj-Napoca, Romania, conduct techno-economic evaluation and life cycle assessment of the process. Tata Steel Consultancy, UK, and SSAB, Sweden, support the project with deeper understanding of the processes and systems involved in modern integrated steel plants. To inform the future commercialisation of the SEWGS technology, a system design and engineering company, Amec Foster Wheeler Italiana, Italy, performs design and costing of a full-size capture plant, using the STEPWISE pilot plant output.

4. The Structure of the Project

The work programme is split across six work packages (WPs) (Figure 4):

- **Work Package 1: Design and construction of the STEPWISE pilot unit.** The objective of this WP is to design, engineer, construct, install and commission the STEPWISE pilot installation. The work is performed in close collaboration between ECN part of TNO and Swerea Mefos. Additional input is provided by Johnson Matthey, Kisuma Chemicals, Amec Foster Wheeler and SSAB. The pilot plant was built and commissioned at the end of 2017. An initial short test campaign was performed to activate catalyst and sorbent materials and establish base performance of the materials. This was followed by the first long pilot plant test campaign.
- **Work Package 2: Testing and development of STEPWISE pilot unit and materials.** This WP is responsible for developing and delivering the active catalysts and sorbent materials that are required in the STEPWISE pilot unit, defining and performing the testing programme of these materials at pilot scale. Kisuma Chemicals is responsible for the development and production of the CO₂ sorbent, while Johnson Matthey is responsible

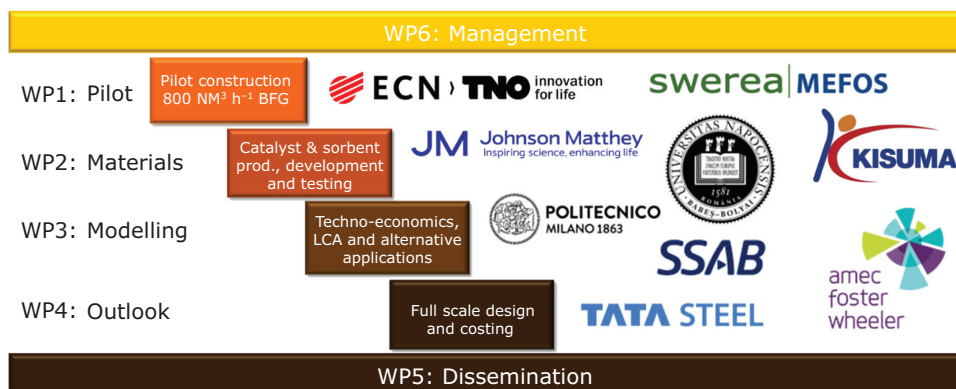


Fig. 4. The STEPWISE project work packages

for the development and production of a WGS catalyst capable of operating with feeds having a decreased steam content and H₂S in the feed. The CO₂ sorbent was produced at tonne-scale using industrial production and pelleting techniques. For the WGS section, the commercial FeCr-based WGS catalyst KATALCO™ 71–6 was identified during lab-scale testing to be suitable for the process.

- Work Package 3: SEWGS modelling and integration in blast furnace plant.** In this WP, STEPWISE cycle optimisation is performed using the validated SEWGS process model with the aim to define the optimal sizing and configuration of the STEPWISE reactor vessels. The optimum layout to minimise the energy efficiency penalties related to CO₂ capture, whilst maximising economic benefits, is evaluated using techno-economic process integration studies to allow comparison with other solutions. Furthermore, the life cycle assessment compares the environmental footprint of the STEPWISE configuration to other CCS solutions that are applicable to the iron and steel industry (for example, gas-liquid absorption). The work is done by Politecnico de Milano and Universitatea Babeş-Bolyai together with ECN part of TNO.
- Work Package 4: Basic process design and cost estimation of full scale SEWGS unit (1500 t_{CO2} day⁻¹) for BFG decarbonisation.** This WP develops a comprehensive exploitation plan for the commercialisation of the outcomes and developments within the project. A basic design and an accurate cost estimate for a full scale plant for CO₂ capture from BFG will be based on the results of long term testing (two pilot plant campaigns). The key outcome will be the development of a business case, including a public engagement strategy for

implementing this technology, as part of the overall communication strategy.

- Work Package 5: Dissemination.** The aim of this WP is to disseminate the objectives and results of the project to a multitude of target audiences, and to encourage the stakeholders to uptake and exploit the project results. Dissemination activities include website maintenance, press releases, meetings, workshops, outreach to industrial platforms, scientific papers, national and international conferences and patents. All project partners contribute to WP5.
- Work Package 6: Management.** The project is managed by the project coordinator, with representatives from each of the WPs and the participating organisations.

5. Pilot Plant

To demonstrate the feasibility of the technology in an industrially relevant environment, the SEWGS pilot plant has been constructed in Luleå, Sweden, next to the SSAB steel manufacturing site (**Figure 5**).

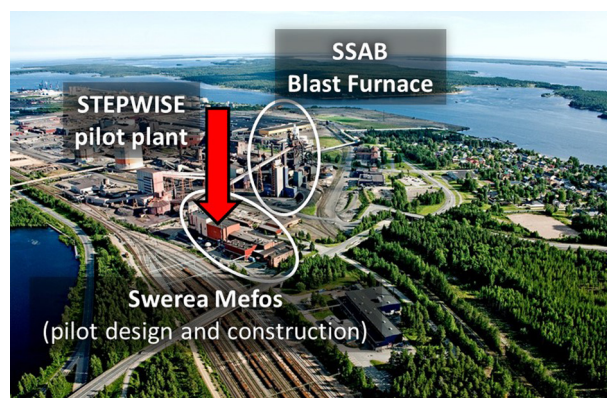


Fig. 5. Overview of the SSAB steel plant and the STEPWISE pilot plant

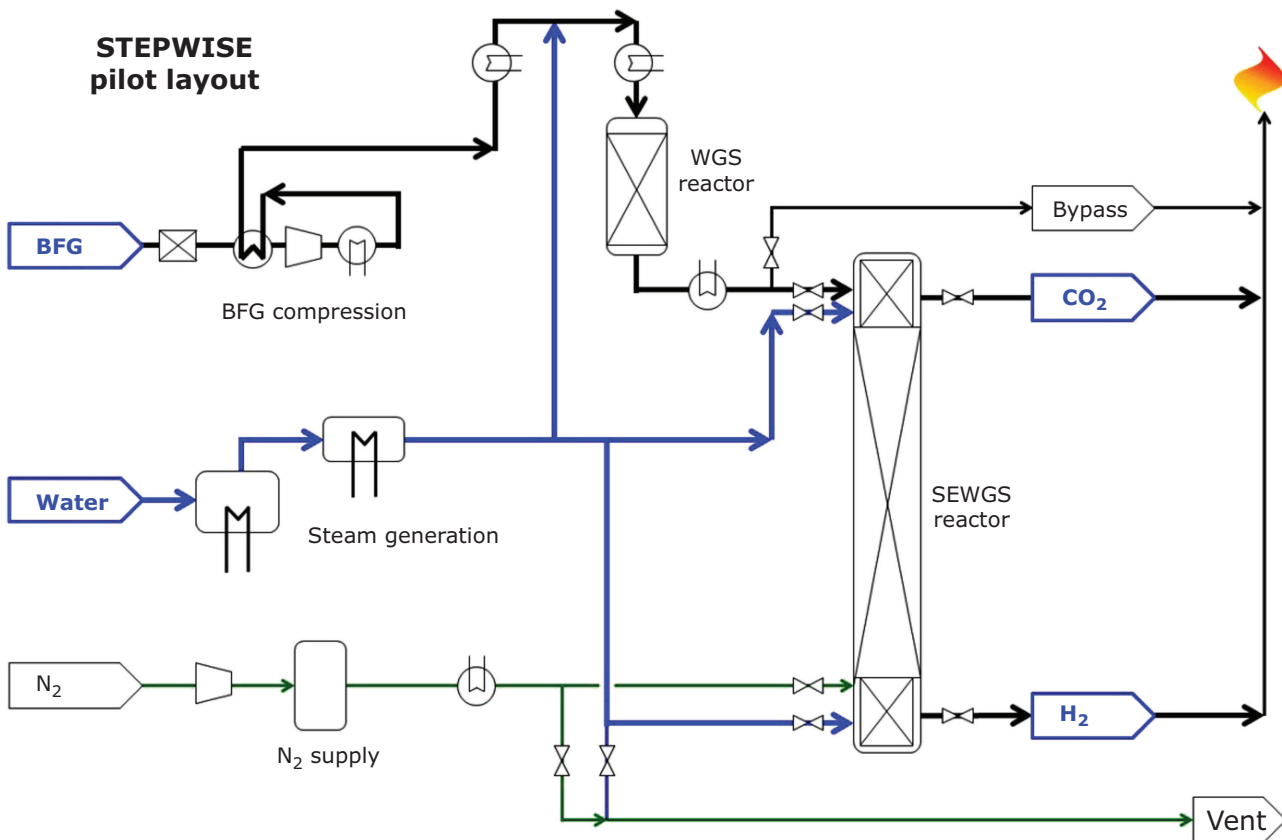
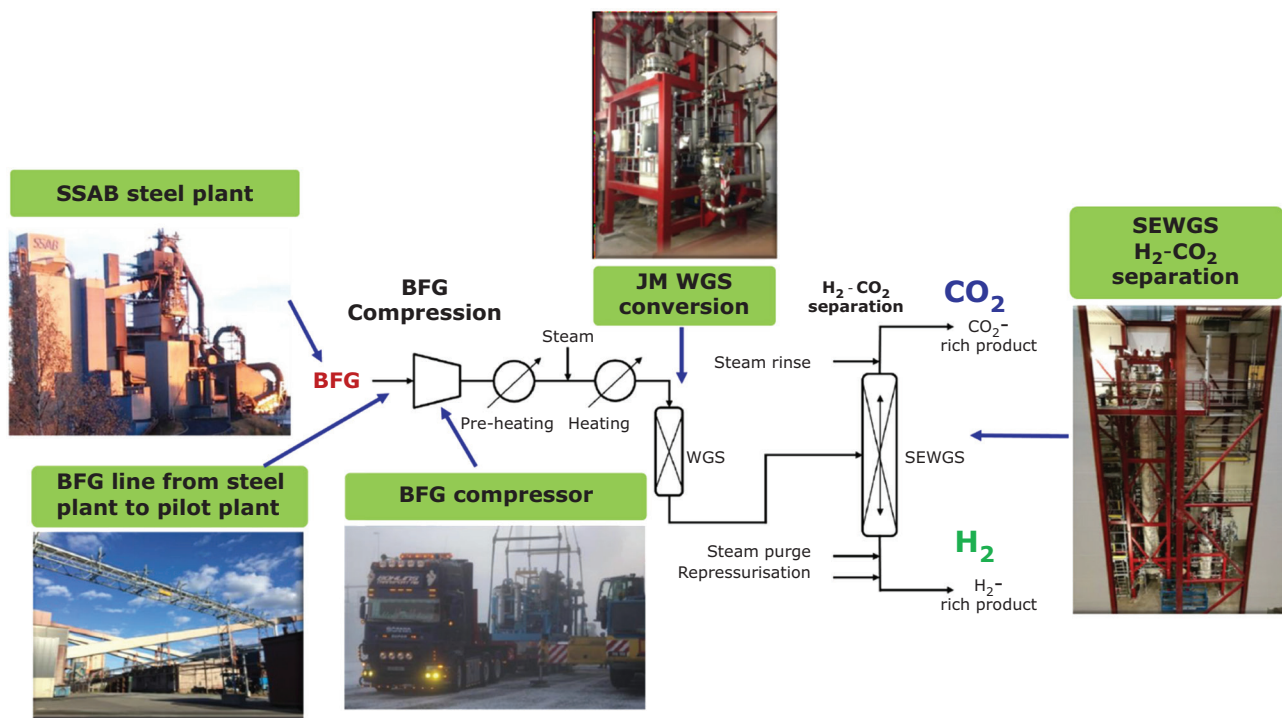


Fig. 6. Pilot plant layout together with photos

The pilot plant receives its BFG feed from SSAB's blast furnace, enabling the technology to reach TRL 6. The pilot plant is designed to process up to 14 tonnes of CO₂ per day. To put that in context, on average a car emits 4.75 tonnes in a year.

Figure 6 represents the layout of the pilot plant. BFG is compressed, pre-heated and steam is added before it enters the WGS reactor. After the WGS reactor, the shifted BFG enters the single column SEWGS reactor, where the feed is separated into H₂-rich and CO₂-rich products. Although SEWGS is a multi-column reactive hot-pressure swing adsorption process, in the pilot, a single column is used to demonstrate the H₂/CO₂ separation. The single column contains about 2.5 tonnes of the sorbent material and is operated in counter-current pressure-swing mode.

Operation of the pilot plant focuses on the steam requirement to obtain the targeted separation efficiency, cycle design, heat management and the interplay between the WGS and the SEWGS sections. The data of the pilot plant will serve as a reference to fine-tune the SEWGS simulation model and the WGS reactor model and will provide an input for cost estimation and scaling up of the SEWGS technology.

6. Summary

The STEPWISE project represents an essential demonstration of the research, development and demonstration trajectory of the SEWGS technology to capture CO₂ from BFG in the iron and steel industry. Scaling up of the SEWGS technology is achieved by international collaboration of the STEPWISE project partners towards design, construction and operation of a pilot plant at Swerea Mefos, Luleå, Sweden, next to the SSAB steel manufacturing site. By increasing the CO₂ capture rate and lowering the specific energy consumption, the project aims at reducing the costs for avoiding CO₂ emissions by 25%.

Acknowledgements

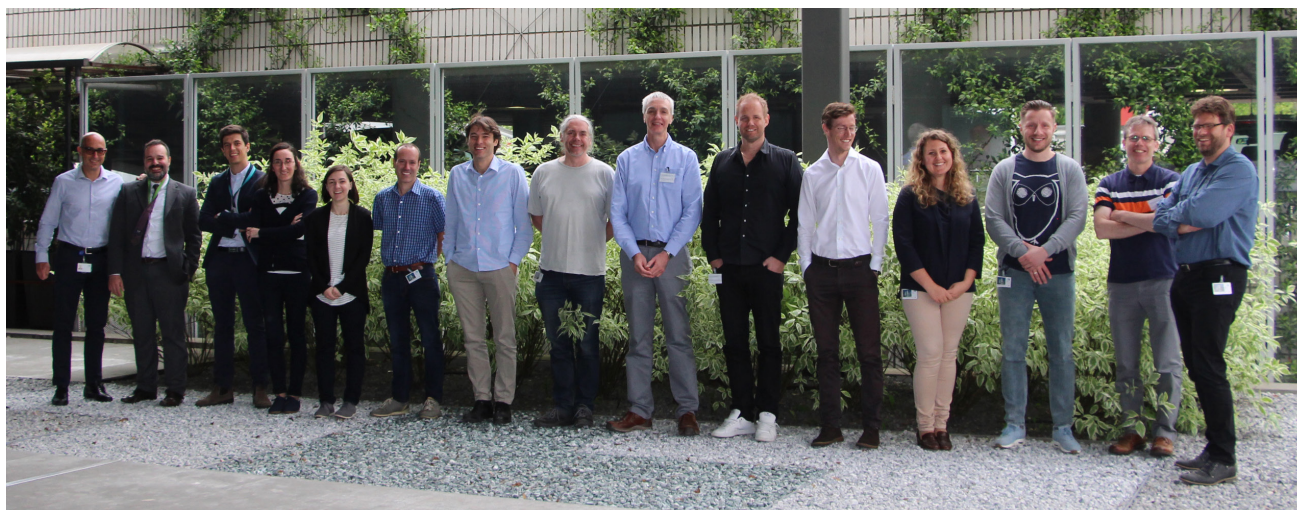
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From left to right: Luca Mancuso (AFW), Federico Consonni (AFW), Fabio Ruggeri (AFW), Letitia Petrescu (UBB), Dora Andreea Chisăliță (UBB), Lawrence Hooey (Swerea Mefos), Giampaolo Manzolini (PTM), Paul Cobden (TNO), Jeremy Johns (TSC), Magnus Lundqvist (Swerea Mefos), David Bellqvist (SSAB), Liliana Lukashuk (JM), Camiel van Dijk (Kisuma), Leon van de Water (JM), Eric van Dijk (TNO).