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Cost effective CO_2 reduction in the Iron & Steel Industry by means of the SEWGS technology: STEPWISE project

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Abstract

In the STEPWISE project, the Sorption Enhanced Water-Gas Shift (SEWGS) technology for CO_2 capture is brought to TRL6 by means of design, construction, operation and modelling a pilot installation in the Iron and Steel industry using Blast Furnace Gas (BFG). This advanced CO_2 removal technology makes use of regenerative solid adsorbents. The STEPWISE project represents the essential demonstration step within the research, development and demonstration trajectory of the SEWGS technology. This project will further reduce the risks associated with scaling up the process.

Peer-review under responsibility of the organizing committee of GHGT-13.

Keywords: Pre-combustion ; CCS ; SEWGS ;adsorption ; pilot testing ; Iron and Steel

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1. Introduction

Several large industrial sectors, such as the Cement and the Iron and Steel industry, cannot significantly reduce their carbon footprint by using renewable energy, and for the near future will need to rely on CCS technology to do so. For the Iron and Steel industry, for example, coal will remain a major fossil fuel required for steel making process for decades to come. Although new steel making processes are being developed in e.g. the ULCOS and COURSE50 programs, a significant reduction of the CO_2 footprint can only be realized by introducing CCS.

The Iron and Steel industry is responsible for an annual emission of ~2.5-3.0 Gt_{CO2}/yr, with up to 10% originating from within the European Union. This represents 6% of total CO_2 emissions, and 16% of total European industrial CO_2 emissions. Typically, Iron and Steel mills are the largest point sources of CO_2 emission within their respective countries. In terms of avoiding serious long term climate change, it is essential that each industrial sector looks to improving energy efficiency and decreasing CO_2 output, as most recently reaffirmed in the COP21 negotiations in Paris.

Although all Iron and Steel mills and the choice of exact process and conditions are location dependent, in general three major process gases are produced; being the Blast Furnace Gas (BFG), Cokes Oven Gas (COG) and Basic Oxygen Furnace Gas (BOFG), of which BFG is by far the largest in volumetric flow, having the lowest caloric value and the highest CO_2 content. All streams are used for energy supply within the Iron and Steel mill and the residual streams are generally used for electricity production, see Fig. 1. In the STEPWISE project, the Sorption Enhanced Water-Gas Shift (SEWGS) CO_2 removal technology is demonstrated in the decarbonization of the BFG stream, generating a CO_2-rich stream intended for storage and a H_2-rich stream intended for electricity production.

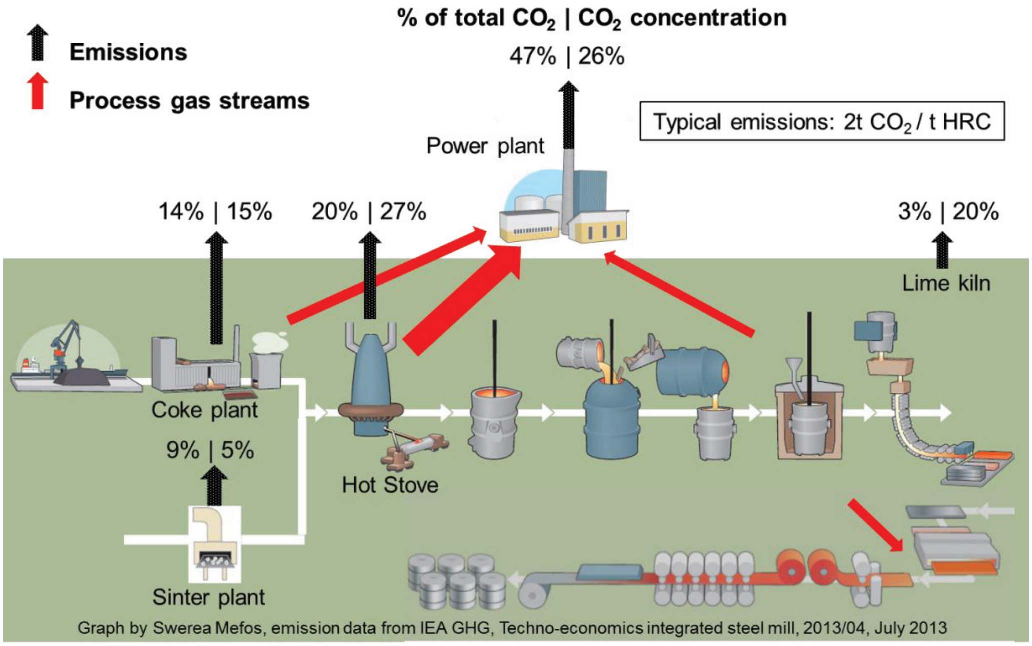

Fig. 1. Schematic representation of an Iron and Steel mill.

In general, the separation of CO_2 and its subsequent transport and storage comes with an energy penalty. The SEWGS technology has the potential of low specific energy consumption for capture, combined with a high CO_2 capture rate and the STEPWISE the project aims at reducing the costs for avoiding CO_2 emissions by 25%. The conservative estimate is that by 2050, a potential cost saving of 750 times the research costs for this project will be realized each year every year, with a much larger potential. The overall objective is to secure jobs in the highly competitive European steel industry, a sector employing 360 thousand skilled people with an annual turnover of €170 billion.

2. The STEPWISE project

2.1. Objectives

The main objective of the STEPWISE project is to scale-up the Sorption-Enhanced Water-Gas Shift (SEWGS) technology for the CO_2 capture from Blast Furnace Gases (BFG), with three overall demonstration goals in comparison to state-of-the-art technologies:

- Higher carbon capture rate – i.e. lower carbon intensity, 85% reduction
- Higher energy efficiency – i.e. lower energy consumption for capture, 60% reduction
- Better economy – i.e. lower cost of CO_2 avoided, 25% reduction

These overall demonstration goals are also illustrated in Fig. 2. In the comparison, the state-of-the-art technology is post combustion amine scrubbing.

The STEPWISE project will achieve this by the construction and the operation of a SEWGS pilot test installation at a blast furnace site enabling the technology to reach TRL6 as the next step in the research, development and demonstration trajectory. This will further reduce the risks associated with scaling-up of technology. Additionally, advanced water-gas shift (WGS) concepts, sorbent production scale-up and endurance testing will be addressed. For the first time, three key components in the required technology chain will be coupled together: an industrial syngas source, subsequent syngas pre-processing with advanced WGS concepts, and finally CO and sulphur component clean-up with simultaneous CO_2 removal in the SEWGS unit.

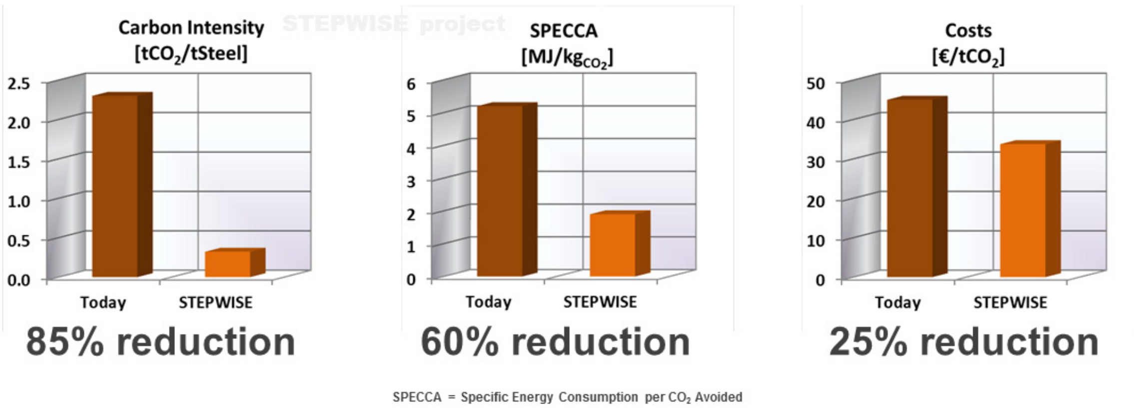

Fig. 2. Demonstration goals for the STEPWISE project.

2.2. Technological approach

The STEPWISE project has at its heart a WGS converter and a SEWGS reactive separator. The WGS converter provides the bulk CO conversion into CO_2 and H_2 via reaction with steam. The subsequent SEWGS technology platform is a solid sorption technology for CO_2 capture from fuel gases in combination with water-gas shift and acid gas removal [1-4]. For pre-combustion CO_2 capture, the SEWGS process scheme is compared with a more conventional wet scrubbing technology in Fig. 3.

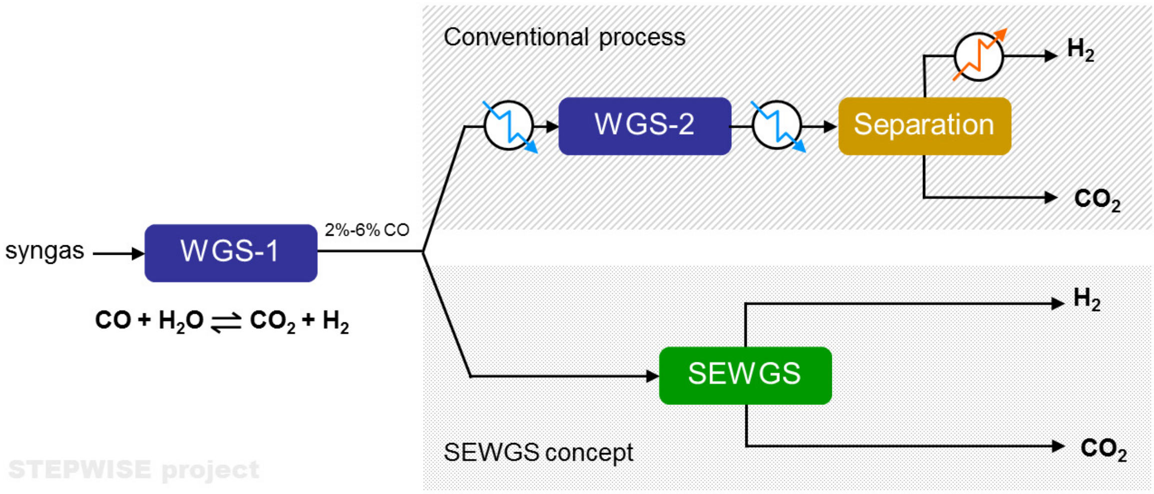

Fig. 3.Process schemes for pre-combustion CO_2 capture. Top: conventional scheme for a wet scrubbing technology. Bottom: scheme for the SEWGS concept.

On the top, the process scheme for the application of a conventional wet scrubbing technology is presented. In case a high CO_2 capture ratio is required, deep CO conversion via the WGS reaction in the pre-shift section needs to be obtained. Typically, two or more WGS reactors in series with inter-stage cooling are needed. The shifted gas needs further cooling prior to entering the wet scrubbing separation step. In case the resulting H_2-rich product is used for power generation, it again needs preheating to improve the efficiency of the electricity production.

The benefits of the SEWGS technology are immediately apparent. First of all, SEWGS is a hot separation technology (350-500°C), meaning that cooling of the shifted gas and the reheating of the H_2-rich product are much less intense or even absent. The sorbent used in the SEWGS process is WGS active and the reaction is combined with the in-situ removal of CO_2, allowing the equilibrium reaction to proceed towards completion. This means that the 2nd WGS reactor can be omitted, the CO_2 capture ratio can be increased and the H_2-production rate is increased. The WGS reaction is an important aspect of both the pre-shift section as the SEWGS section, and it allows varying the degree of WGS conversion between the units. Since steam is required for the WGS reaction and steam addition directly contributes to the efficiency loss of the subsequent power plant, this WGS-SEWGS flexibility allows minimization of the overall steam consumption and advanced WGS concepts can be implemented [5].

The heart of the SEWGS technology is the hydrotalcite-based sorbent. K-promoted hydrotalcite are known for their good hydrothermal stability and fast sorption kinetics [6,7]. Moreover, these materials are chemically very robust, active for the WGS reaction and co-capture other acid gas components next to CO_2 such as H_2S+COS [4].

Upon feeding of the shifted gas to the SEWGS reactor at 400°C and 25 bar, the sorbent is active for the WGS reaction and adsorbs CO_2 and H_2S. In this step a hot H_2-rich product at pressure is produced. Once the sorbent within the reactor approaches saturation with adsorbed CO_2, the material is regenerated by means of a release of pressure and flushing with superheated steam. After repressurization of the column, the cycle can again start. The

SEWGS technology thus represents a reactive hot-PSA system, as schematically represented in Fig. 4. Compared to conventional H_2-PSA, the hot SEWGS technology can use a small amount of steam as 3rd component to drive the separation between H_2 and CO_2. Accordingly, a high CO_2 product purity (heavy product) can be combined with a high H_2 recovery (light product), a feature not possible in conventional cold PSA. To minimize the CO_2 capture penalty, the SEWGS sorbent and cycle design must be tuned to minimize the steam requirement for a given CO_2 purity and CO_2 capture ratio.

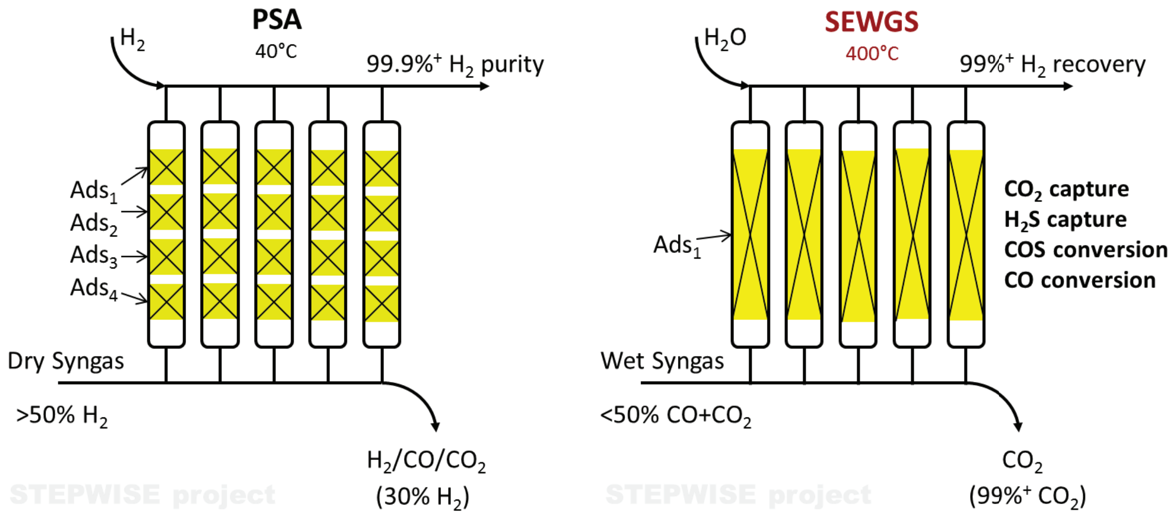

Fig. 4. Schematic comparison of the SEWGS technology with a H_2-PSA.

In the pre-shift section, deep CO conversion is not required and advanced WGS concepts such as split flow operation can be applied. In split flow WGS operation, part of the feed stream bypasses the 1st WGS reactor and is mixed with the effluent of this 1st reactor to be fed in the 2nd reactor. This allows to reduce the overall amount of steam required to reach a certain CO conversion [5]. The steam savings, naturally, should outweigh the costs of the additional hardware.

2.3. Consortium and project lay-out

The STEPWISE consortium ready to achieve the project goals consists of 9 partners from 5 European member states. The partners in the consortium represent the whole value chain from technology provider, to material suppliers, to technology contractor, to industrial end-user from the European steel sector.

In Fig. 5, the project lay-out is presented, together with the logos of the partners involved. Besides the overarching dissemination and project management tasks, the work packages concern:

- Pilot design, construction and operation.
  Principal partners being Swerea Mefos and ECN.
- Catalyst and sorbent material development, production and testing.
  Principal partners being Johnson Matthey, Kisuma Chemicals and ECN.
- Process evaluation by means of techno-economic evaluation and life-cycle assessment.
  Principal partners being Politecnico de Milano, Universitatea Babes-Bolyai, ECN, Tata Steel Consulting and SSAB.

- Design and costing of a full size capture plant.
  Principal partners being Amec Foster Wheeler Italiana, Tata Steel Consulting and SSAB.

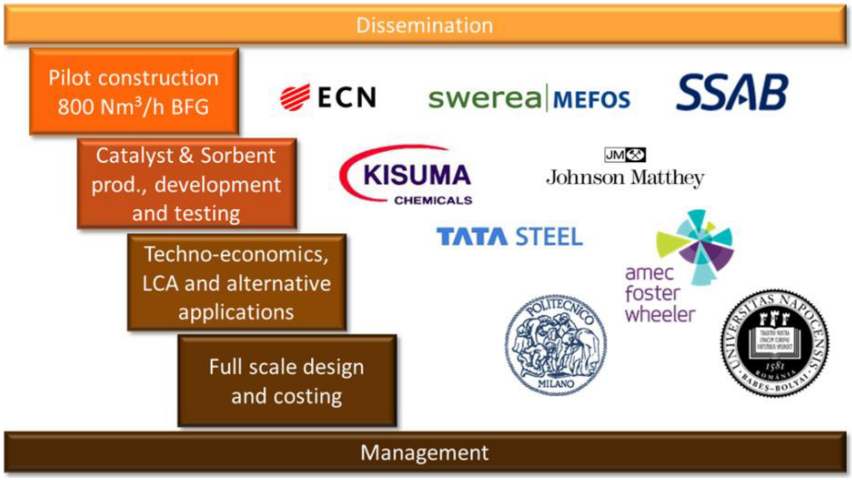

Fig. 5. Project structure and partners.

In the work package on pilot design, construction and operation, the design teams of Swerea Mefos (Sweden) and ECN (The Netherlands) work closely together, aiming at the construction of the pilot at the facilities of Swerea Mefos in Luleå, northern Sweden. Their facilities are next door to the SSAB (Sweden) blast furnace, see Fig. 6, from which the pilot will receive its BFG feed gas. ECN is the SEWGS technology provider and is responsible for the design of the reactor skids, while Swerea Mefos is building the required infrastructure. The most important component of the infrastructure is the BFG compressor. Upon completion of the reactors in The Netherlands, these skids will be shipped to Swerea Mefos, where they will be integrated into the infrastructure. Throughout the different design phases, the material suppliers are consulted to optimize for material delivery, material handling and safe operation of the reactors. The pilot is designed for a 800 Nm^3/h BFG feed, having an average dry composition of 19% CO, 25% CO_2, 3% H_2, 20 ppm H_2S+COS and 53% N_2. Accordingly, the STEPWISE pilot has the capability of processing up to 15 tonnes CO_2 per day. Compared to the lab-scale development of the SEWGS technology at ECN, the STEPWISE pilot scale-up is a factor 500 with respect to the required amount of sorbent.

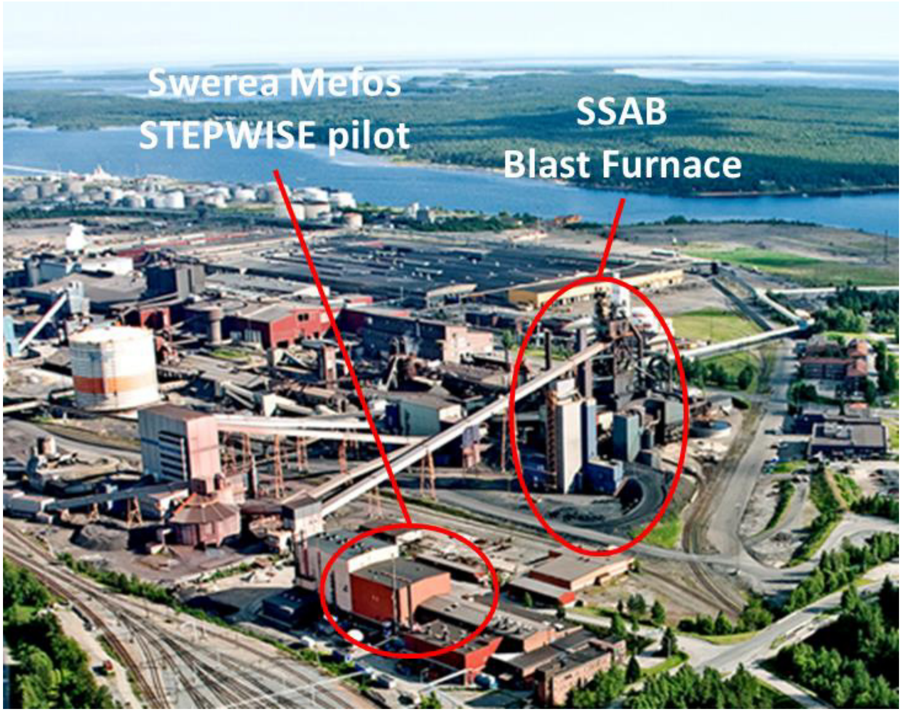

Fig. 6. Picture of the Swerea Mefos and SSAB sites in Luleå, Sweden.

In the work package on the catalyst and sorbent material development, production and testing, Johnson Matthey (United Kingdom) is responsible for the WGS catalyst and Kisuma Chemicals for the CO_2 sorbent. For the WGS section, the application potential of commercial FeCr-based catalysts is explored, while in parallel alternative sulphur resistant catalysts are being developed that are capable of operation with low steam feeds. The WGS operational regime for a BFG feed is very different from conventional WGS operation in the chemical industry. BFG is much leaner in H_2 and contains low levels of H_2S and COS. Exploration of the operability limits of conventional FeCr-based catalysts at these conditions is thus justified. Pilot testing of FeCr-based catalysts for decarbonisation of syngas originating from the Buggenum IGCC in the Nuon Catch-Up project suggested possible improved operability for this class of unconventional feeds [8,9].

ECN and Kisuma Chemicals (The Netherlands) have been developing K-promoted MgO-Al_2O_3 hydrotalcite based materials already for a number of years. Kisuma Chemicals is the largest producer of specialty Magnesium minerals in Europe, such as $Mg(OH)_2$ and hydrotalcites. Typically, these materials are used as flame retardants in polymer applications. In the STEPWISE project, Kisuma Chemicals produces a BFG tuned sorbent using their industrial production facilities giving a clear insight into the technical challenges and cost aspects of producing this material at tonnage scale. Two reactor fillings for the two testing campaigns are foreseen, each involving approximately 3 tonnes of sorbent.

The Politecnico de Milano (Italy) and the Universitatea Babes-Bolyai (Romania) are performing the techno-economic and the life-cycle analyses. The SEWGS based technology is compared with alternative CO_2 capture technologies on technical, economic and environmental impact, also in relation to a no-capture Iron and Steel mill. Politecnico de Milano has a vast track record in comparing pre- and post-combustions CCS technologies in the context of power production and iron and steel making [10-13]. Universitatea Babes-Bolyai has been involved in

LCA aspects of CCS technologies in the field of gasification and chemical looping [14,15]. Besides the greatly reduced GHG-impact of CCS technologies, their energy and materials requirements induce other increased environmental impacts. As SEWGS has a low energy requirement for CO_2 capture and uses benign solid materials, SEWGS technology has the potential to differentiate on these other environmental impacts compared to alternative CCS technologies. The results from the STEPWISE pilot testing will be fed into these studies, yielding valuable updates.

Amec Foster Wheeler Italiana (Italy), with their experience designing IGCC plants, gas turbine combined cycle power plants and hydrogen plants and deep knowledge on technologies for CO_2 capture, guides the study on the large-scale SEWGS-integrated plant. Together, SSAB and Tata Steel Consulting (United Kingdom) as the end-users are able to support the project with deeper understanding of the processes and process systems involved in modern integrated steel plants. They are the parties that can value the comparison of the SEWGS technology with alternative technologies to reduce the CO_2 footprint of today's and future steel plants.

All partners in the consortium are committed to proactive participate in the dissemination and information exchange with stakeholders and other CCS technology developments.

3. Results achieved

In this initial stage of the STEPWISE project, the focus is on the design of the pilot (WP1) and on the development of the required materials (WP2).

In the design of the pilot, the following stages have been completed:

- Common Design Practice was defined to align the activities of the various partners involved in the design, construction, operation and decommissioning of the STEPWISE pilot unit.
- Basis of Design describes the minimum technical requirements and site specific data for design, engineering, supply of materials and equipment, fabrication, delivery to the construction site, unit assembling, commissioning, operation and decommissioning of the STEPWISE Pilot unit.
- Basic Design further details the requirements for the pilot installation.
- Detailed Design fixes the pilot lay-out and finalizes the functional specifications of all equipment to start the procurement and construction. Long lead items are identified early in the process and special attention is given to define their technical specifications to allow timely procurement. This concerns the BFG compressor, together with the steam boiler, reactors and N_2 compression system.

In Fig. 7 the fixed pilot lay-out is represented. It comprises of BFG compression, followed by a catalytic WGS converter optimizing for CO conversion to CO_2 and H_2, and a single column SEWGS reactor to effect the CO_2-H_2 separation.

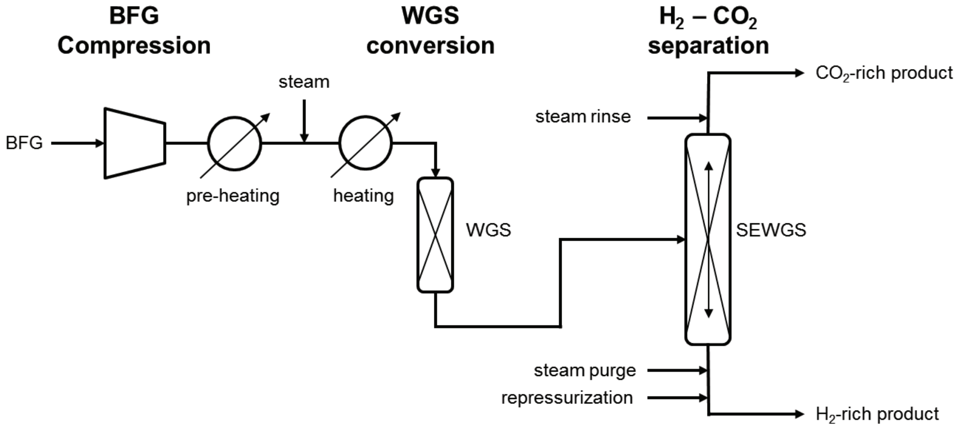

Fig. 7. Schematic layout of the STEPWISE pilot.

For the WGS section, a commercial Iron-Chromium-based catalyst is available and an alternative catalyst is under development. The suitability of the commercial catalyst under the atypical conditions for BFG operation has been established, illustrating the catalyst robustness at the low sulphur conditions associated with BFG. The novel catalyst has been shown to be suitable for low steam operation.

For the SEWGS section, the chemical composition of the potassium promoted Magnesium-Aluminium-based sorbent is optimized to improve its long term behavior. This material is produced at 12 tonnes scale using industrial production routes.

Reactor modelling as well as system modelling, economic assessments and life cycle analyses are essential to demonstrate the potential of the STEPWISE SEWGS technology and for its further roll-out. Calibration of the existing SEWGS reactor model identified the focal areas for model tuning and a start was made to define the base case and reference cases for the techno-economic assessment. An inventory of the characteristics of the different unit operations relevant for the life-cycle-analysis has also started.

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References

[1] van Selow E.R., Cobden P.D., Verbraeken P.A., Hufton J.R., van den Brink R.W., Carbon Capture by Sorption-Enhanced Water−Gas Shift Reaction Process using Hydrotalcite-Based Material, Ind. Eng. Chem. Res., 48 (9) (2009) 4184–4193

[2] Boon J., Cobden P.D., van Dijk H.A.J., Hoogland C., van Selow E.R., van Sint Annaland M., Isotherm model for high-temperature, high-pressure adsorption of CO_2 and H_2O on K-promoted hydrotalcite, Chem. Eng. J. 248 (2014) 406–414

[3] Boon J., Cobden P.D., van Dijk H.A.J., van Sint Annaland M., High-temperature pressure swing adsorption cycle design for sorption-enhanced water–gas shift, Chem. Eng. Sci. 122 (2015) 219–231

[4] van Dijk H.A.J., Walspurger S., Cobden P.D., van den Brink R.W., de Vos F.G., Testing of hydrotalcite-based sorbents for CO_2 and H_2S capture for use in sorption enhanced water gas shift, Int. J. of Greenhouse Gas Control 5 (2011) 505-511

[5] Carbo M.C., Boon J., Jansen D., van Dijk H.A.J., Dijkstra J.W., van den Brink R.W., Verkooijen A.H.M., Steam demand reduction of water–gas shift reaction in IGCC power plants with pre-combustion CO_2 capture, Int. J. of Greenhouse Gas Control 3 (6) (2009) 712–719

[6] Lee K. B., Verdooren A., Caram H. S., Sircar S, Chemisorption of carbon dioxide on potassium-carbonate-promoted hydrotalcite., J. Colloid Interface Sci. 308 (1) (2007) 30–9

[7] Oliveira E.L.G., Grande C.A., Rodrigues A.E., CO_2 sorption on hydrotalcite and alkali-modified (K and Cs) hydrotalcites at high temperatures, Sep. Purif. Technol. 62 (2008) 137–147
[8] van Dijk H.A.J., Cohen D., Hakeem A.A., Makkee M., Damen K., Validation of a water–gas shift reactor model based on a commercial FeCr catalyst for pre-combustion CO_2capture in an IGCC power plant, Int. J. of Greenhouse Gas Control 29 (2014) 82–91
[9] Trapp C. Thomaser T., van Dijk H.A.J., Colonna P., Design optimization of a pre-combustion CO_2 capture plant embedding experimental knowledge, Fuel 157 (2015) 126–139
[10] Gazzani M., Macchi E., Manzolini G. CO_2 capture in integrated gasification combined cycle with SEWGS – Part A: Thermodynamic performances, Fuel 105 (2013) 206-219
[11] Manzolini, G., Macchi E., Gazzani M. CO_2 capture in Integrated Gasification Combined Cycle with SEWGS – Part B: Economic assessment, Fuel 105 (2013) 220-227
[12] Gazzani M., Macchi E., Manzolini G., CO_2 capture in natural gas combined cycle with SEWGS. Part A: Thermodynamic performances, Int. J. of GreenhouseGas Control 12 (2013) 493–501
[13] Manzolini G., Macchi E., Gazzani M., CO_2 capture in natural gas combined cycle with SEWGS. Part B: Economic assessment, Int. J. of Greenhouse Gas Control 12 (2013) 502–509
[14] Petrescu L., Cormos C.C., Waste reduction algorithm applied for environmental impact assessment of coal gasification with carbon capture and storage, J. Clean. Prod. 104 (2015) 220-235
[15] Petrescu P., Müller C.R., Cormos C.C., Life cycle assessment of natural gas-based chemical looping for hydrogen production, Energy Procedia 63 (2014) 7408-7420