International Journal of Greenhouse Gas Control 94 (2020) 102935

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Techno-economic assessment of SEWGS technology when applied to integrated steel-plant for CO_2 emission mitigation

G. Manzolini[a,*], A. Giuffrida[a], P.D. Cobden[b], H.A.J. van Dijk[b], F. Ruggeri[c], F. Consonni[c]

[a] Politecnico di Milano, Dipartimento di Energia, via Lambruschini 4, 20126, Milano, Italy
[b] TNO, Westerduinweg 3, 1755 LE, Petten, the Netherlands
[c] Wood (formerly Amec Foster Wheeler Italiana), Via S. Caboto 15, 20094, Corsico, Italy

ARTICLE INFO

Keywords:
Sorption Enhanced Water Gas Shift
CO_2 capture
Iron and steel industry
SPECCA
Cost of CO2 avoided
Techno-economic assessment

ABSTRACT

Mitigation of CO_2 emissions in the industrial sector is one of the main climate challenges for the coming decades. This work, carried out within the STEPWISE H2020 project, performs a preliminary techno-economic assessment of the Sorption Enhanced Water Gas Shift (SEWGS) technology when integrated into the iron and steel plant to mitigate CO_2 emissions. The SEWGS separates the CO_2 from the iron and steel off-gases with residual energy content (i.e. Blast Furnace Gas, Basic Oxygen Furnace Gas and Coke Oven Gas) and the produced H_2 is sent to the power generation section to produce the electricity required by the steel plant, while the CO_2 is compressed and transported for storage. Detailed mass and energy balances are performed together with a SEWGS cost estimation to assess the energy penalty and additional costs related to CO_2 capture. Results demonstrates the potential of SEWGS to capture over 80 % of CO_2 in the off-gases, which results in entire plant CO_2 emission reduction of 40 % with a Specific Energy Consumptions for CO_2 Avoided (SPECCA) around 1.9 MJ/kgCO_2. SEWGS outperforms a commercial amine scrubbing technology which has a SPECCA of 2.5 MJ/kgCO_2 and only 20 % of CO_2 avoided. The cost of CO_2 avoided calculated on the basis of a fully integrated steel plant is around 33 €/t_{CO2} compared to 38 €/t_{CO2} of the amine technology.

1. Introduction

The reduction of CO_2 emissions to the atmosphere is a major challenge that must be addressed in the upcoming years. The industrial sector is one of the most emission-intensive sectors, but it also has a significant potential to reduce its carbon footprint. In particular, the steel industry, which accounts for 6 % of total CO_2 emissions and 16 % to total industrial emissions of CO_2 worldwide, has a large potential to reduce emissions. Around 50 % of the overall CO_2 emissions of a steel plant are emitted from the power generation section which uses Basic Oxygen Furnace (BOFG), Coke Oven (COG) and Blast Furnace gases (BFG) as fuel (see Fig. 1 for the typical integrated steel plant lay-out). These flue gases consist of CO and H_2 mixed with inerts and their energy content is used in the power generation section to cover the plant electricity demand with an excess electricity usually sold to the grid. The remaining CO_2 emissions are distributed across several locations in the steel plant (i.e. coke oven batteries, sinter plant, hot stoves): these emissions are diluted with N_2 and O_2 (Santos, 2019; Gazzani et al., 2015).

1.1. CO_2 capture in integrated steel plants

When CO_2 capture technologies are applied to an integrated steel plant, the focus can either be on the power generation section only or on the power generation section plus the other main emission points. The former is the most convenient option from both energy and economic points of view as the CO_2 is concentrated and located in one stream, but this limits the CO_2 abatement potential to 50 % of the overall plant emissions. In fact, CO_2 capture from other emission points is both more challenging and more expensive (Santos, 2019).

The IEA-GHG report investigated the use of CO_2 capture in integrated steel plants (Santos, 2019), with reference to post-combustion and oxygen-blown blast furnace technologies. The study calculated a higher energy consumption related to CO_2 capture by 20 % compared to the reference plant without any CO_2 abatament technology. (Arasto et al. (2014)) assessed the performance of oxygen-blown blast furnace technology. They showed a potential CO_2 emission reduction of 68 % and outlined the risks of developing a brand new concept for iron and steel production. A second paper showed that the oxygen blast furnace technology for CO_2 capture is convenient from economic point of view

* Corresponding author.
E-mail address: giampaolo.manzolini@polimi.it (G. Manzolini).

https://doi.org/10.1016/j.ijggc.2019.102935
Received 28 February 2019; Received in revised form 9 December 2019; Accepted 9 December 2019
Available online 23 December 2019

Nomenclature

Acronym

BFG	Blast Furnace gases
BOFG	Basic Oxygen Furnace gas
BOP	balance of plant
C	Cost
CCA	Cost of CO_2 avoided [€/t_{CO2}]
CCR	CO_2 Capture Ratio [%]
CCS	Carbon Capture and Storage
CEPCI	Chemical Engineering Plant Cost Index
COG	Coke Oven Gas
E	Specific emissions [kg_{CO2}/kWh_{el} or t_{CO2}/t_{HRC}]
EBTF	European Benchmarking Task Force
EPC	Energy and procurement cost
EXP	Expander lay-out
f	Scaling factor
FG	fuel gas
GHG	greenhouse gas
GT	gas turbine
GTCC	Gas Turbine Combined Cycle
HP	High Pressure
HRC	Hot Rolled Coil
HRSC	Heat recovery steam cycle
HRSG	Heat recovery steam generator
HTS	High Temperature Shift
IC	Indirect cost
IEA	International Energy Agency
IP	Intermediate pressure
KPI	Key Performance Indicators
L	liquid (as subscript)
LCOE	Levelized Cost of Electricity
LHV	lower heating value [MJ/kg]
LP	Low pressure
m	mass flow rate [kg/s]
MEA	monoethanolamine
OpEx	Operating Expenditure
p	pressure [bar]
PEC	Primary Energy Consumption [GJ/t_{CO2}]
PP	Power plant (as subscript)
Ref	Reference case
RH	Reheater
S	Size
SAT	Saturator lay-out
S/C	Steam-to-Carbon ratio
SEWGS	Sorption Enhanced Water Gas Shift
SH	Superheater
SM	Steel Mill (as subscript)
SPECCA	Specific Energy Consumptions for CO_2 Avoided [MJ/kg_{CO2}]
ST	Steam Turbine
T	temperature [°C]
TDPC	Total Direct Plant Cost
TEC	Total Equipment Cost
TGR	Top Gas Recycling
TIC	Total Installation Cost
TIT	Turbine Inlet Temperature [°C]
TPC	Total Plant cost
TRL	Technology Readiness Level
U·S	heat transfer coefficient [MW/K]
V	Vapour (as subscript)
WGS	Water Gas Shift

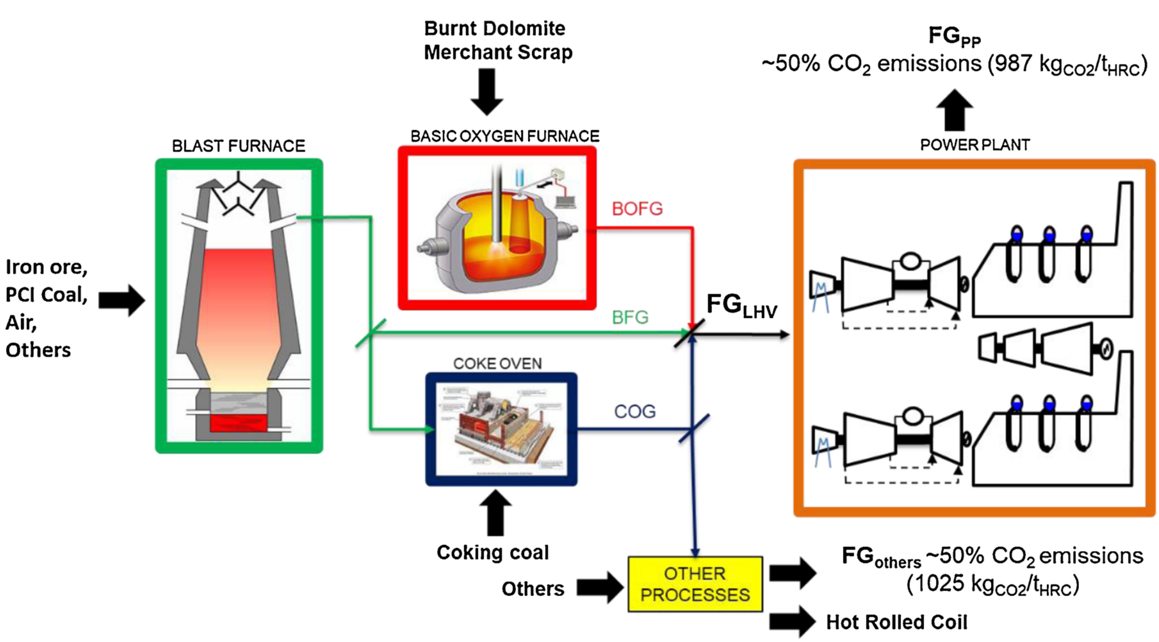

Fig. 1. Schematic representation of the integrated steel plant.

only for carbon tax above 50 €/t_{CO2} (Tsupari et al., 2015). For the sake of reference, the CO_2 emission price in 2017 was around 15 €/t_{CO2} (Pfahler et al., 2008) and equal to 22 €/t_{CO2} in the beginning of 2019 (CO2 emission trading, 2018). A more recent study (Jin et al., 2017) confirmed the potential of oxygen blast furnace in terms of CO_2 emission reduction.

The European Ultra-Low CO_2 Steelmaking (ULCOS) project proposed several novel Carbon Capture and Storage (CCS) routes aimed at reducing the CO_2 emissions by at least 50 % (Pardo et al., 2013).

Top Gas Recycling (TGR) consists in injecting pure O_2 or enriched air instead of air into the furnace (therefore significantly reducing the presence of N_2 in the BFG). This practice is identified as one of the most promising technologies and brings about two main advantages: (i) the higher concentration of CO_2 in the top gas for a simplified separation and (ii) the reducing gases (CO and H_2) can be sent back to the blast furnace, lowering the coke demand. Thus, the CO_2 emissions can be reduced by 76 % overall. This value is optimistic as it was determined neglecting additional fuel consumption and energy required for other processes and O_2 production respectively. Another EU project (ASCENT) investigated the application of Ca-Cu chemical looping process to a steel mill (Martínez et al., 2018). The new concept can reduce the CO_2 emission by 31 % with a Specific Energy Consumption for CO_2 Avoided (SPECCA) of 2.6 MJ/kg_{CO2} if no additional energy source (natural gas) is used. The use of CO_2 membranes to steel plants was investigated by (Baker et al. (2018)), who calculated a cost of 40–50 €/t_{CO2} for around 80 % of CO_2 capture ratio. Additionally, the combination of membranes and amine scrubbing for CO_2 capture in integrated steel plants was also considered by (Chung et al. (2018)) with CO_2 avoidance between 55 % and 65 %.

The above-mentioned studies demonstrate the interest in reducing the carbon footprint of steel making process worldwide. Yet, the results cannot be compared directly, as both the methodology and the assumptions are not consistent.

1.2. SEWGS technology

Pre-combustion CO_2 removal from a fuel gas involves the conversion of CO into CO_2 and H_2 via reaction with steam, followed by separation of the CO_2.

Fig. 2 compares a Sorption Enhanced Water Gas Shift (SEWGS) process scheme with a more conventional wet scrubbing technology. The top scheme in Fig. 2 represents a conventional wet scrubbing technology, which requires deep CO conversion in the water-gas shift (WGS) section to obtain a high CO_2 capture ratio. Besides this intensive WGS conversion, the shifted gas needs to be cooled prior to entering the wet scrubbing separation section. In case the resulting H_2-rich product is used for power generation, it needs reheating again to improve the efficiency of the electricity production. The SEWGS technology illustrated in the bottom scheme of Fig. 2 is a hot separation technology based on pressure swing adsorption using a solid sorbent (Van Selow et al., 2009; Van Dijk et al., 2011a; Boon et al., 2015, 2014). The benefits of the SEWGS technology are immediately apparent: much less heating and cooling are required, while the WGS activity of the sorbent allows for a smaller pre-shift section and an overall complete CO conversion. Based on experimental SEWGS demonstration (Van Selow et al., 2009; Van Dijk et al., 2011a; Boon et al., 2015, 2014), a system analysis quantified these benefits for IGCC power decarbonization, where the SEWGS concept showed a considerably lower SPECCA of 2.5 MJ/kg_{CO2} compared to 3.7 MJ/kg_{CO2} obtained when using Selexol in pre-combustion mode with similar CO_2 avoidance rates (Gazzani et al., 2013a), or even 4.2 MJ/kg_{CO2} for post-combustion schemes in a pulverized-coal power plant layout.

The heart of the SEWGS technology is a hydrotalcite-based sorbent. In particular, K-promoted hydrotalcite is known for good hydrothermal stability and fast sorption kinetics (Lee et al., 2007; Oliveira et al., 2008; Coenen et al., 2017). Moreover, these materials are chemically very robust, active for the WGS reaction and co-capture other acid gas components along with CO_2, such as H_2S and COS (Van Dijk et al., 2011b). The sorbent is operated in loading and regeneration cycles, using a pressure swing adsorption approach. It utilises steam to enhance the recovery of both H_2 and CO_2. In the feeding step, the sorbent is active for the WGS reaction and adsorbs CO_2 and H_2S, producing a hot and pressurized H_2-rich product. Once sorbent saturation is nearing completion, the material is regenerated by means of releasing the pressure and purging with superheated steam, producing a hot low-pressure CO_2 product. Prior to the pressure release, rinse steam is added to enhance the CO_2 product purity. In order to minimize the CO_2 capture penalty, the SEWGS sorbent and cycle design must be tuned to minimize the steam requirement for given CO_2 purity and CO_2 capture ratio.

1.3. Objective of the work

This work assesses performance and cost of the SEWGS process compared to a base case (steel plant without CO_2 capture) and to a reference case (steel plant with CO_2 capture using amine scrubbing), in order to determine the potential of the SEWGS technology. It is a follow-up of a previous study, as the SEWGS performance has now been updated with the latest experiments carried out in the European H2020 STEPWISE project and economic calculations have also been performed (Gazzani et al., 2015). In the STEPWISE project, the SEWGS technology for CO_2 capture is brought to an advanced technology readiness level (TRL6) by means of design, construction, operation and modelling of a pilot installation in the Iron and Steel industry using actual Blast Furnace Gas (BFG) (Van Dijk et al., 2018). This advanced CO_2 removal technology makes use of regenerative solid adsorbents. The CO_2 removal section is comprised of a single stage pre-shift unit to perform the bulk of the CO conversion to CO_2 and H_2, followed by a SEWGS section consisting of multiple columns operating in pressure-swing mode (Van Selow et al., 2009; Van Dijk et al., 2011a). The solid adsorbent interacts with CO_2 and acid gases like H_2S, producing a decarbonised fuel gas and is regenerated at low pressure using a steam purge producing a CO_2 stream for capture or even utilisation.

This work focuses on the SEWGS integration with the power generation section only, as it is a viable short term solution and the most beneficial from the current economic perspective. This work is divided as follows: Section 2 presents the methodology adopted for the technology assessment, Section 3 introduces the base and reference cases, along with the two cases integrating the SEWGS technology, Section 4 reports the main results and Section 5 draws the conclusions of the work and anticipates future developments.

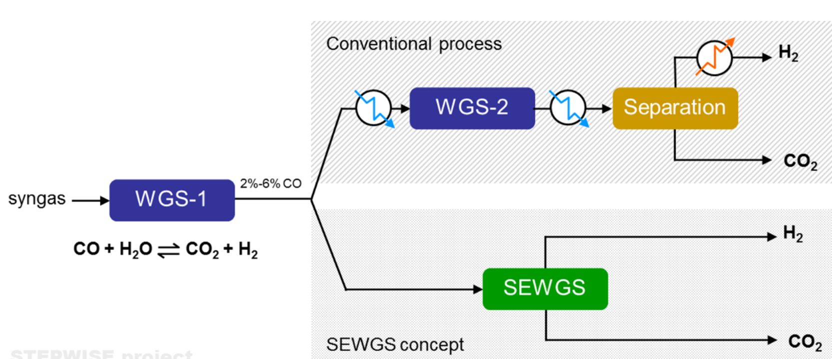

Fig. 2. Process schemes for pre-combustion CO_2 capture. Top: conventional scheme for a wet scrubbing technology. Bottom: scheme for the SEWGS concept.

2. Methodology

This section reports both the thermodynamic and economic assessment methodologies, with the related assumptions. Attention is paid to the definition of the key performance indicators.

2.1. Thermodynamic assessment methodology and assumptions

Mass and energy balances of the plants considered in the current work have been estimated using the proprietary code GS, which was developed by the GECOS group of Politecnico di Milano to assess the performance of gas/steam cycles as well as a variety of other plant options including Integrated Gasification Combined Cycle, membranes, fuel cells and sorbent based systems (Chiesa and Macchi, 2004; Chiesa et al., 2005; Kreutz et al., 2005). The code is conceived for the prediction of gas turbine performance at the design point and includes the one-dimensional design of the turbine, functionality to calculate the fluid expansion through a stage-by-stage approach, estimating the cooling flow rates and the evolution of the cooled expansion. This gas turbine calculation approach represents a significant added value for this study, where the gas turbine is fed with non-conventional fuels and the expansion and blade cooling requirements are calculated considering the actual composition of the combustion gas. The main assumptions for the components of the power generation section are summarized in Table 1.

The S/CO ratio at the inlet of the Water Gas Shift reactor is set equal to 1.5 consistent with the latest experiments performed in Sweden at the STEPWISE demo plant.

As regards the SEWGS performance, a dedicated model developed by TNO has been adopted and then integrated in the GS model for the entire plant simulation. In particular, TNO has developed a detailed model that describes the relevant phenomena occurring during all the different steps of the cycle (Van Selow et al., 2009; Van Dijk et al., 2011a; Boon et al., 2015, 2014). The model consists of (i) an interaction module, describing the interactions of the different gas-phase components with the sorbent material over a wide range of conditions that cover all the different steps, (ii) a mass-transfer module, describing the kinetics of uptake and release by means of a k_{LDF} model (Ruthven, 1982) and (iii) a column module, describing the packed bed behavior and allowing effective accounting of the performance of the different columns in the cycle. In this study, especially the interaction module was significantly revised, based on new insights on the types of sites involved (Coenen et al., 2017, 2019) and the learnings from the pilot operation.

The current version of the model is capable of describing the pilot results adequately in terms of capture rate and overall CO_2 purity. This is illustrated in the following examples. Fig. 3 reports the carbon capture ratio as measured in the STEPWISE demo plant as a function of the blow-down pressure for a $1.1-15$ bar cycle using a BFG feed. Using the pilot settings, the model results are given by the open symbols, illustrating the adequacy of the model. The same figure also reports the CO_2 purity measured in the pilot plant as a function of the length of the rinse step. The CO_2 product results from the CO_2 released during the Blow-Down step and the Purge step. It is observed that the current model adequately describes the overall CO_2 purity, while the Blow-Down purity is somewhat under-predicted and the Purge CO_2 purity somewhat over-predicted. These examples illustrate that the overall behavior of the single column pilot plant is well described, but that some aspects still require further fine-tuning.

Two scenarios are considered in Table 2, where the main difference being the final CO_2 purity produced by the system.

Cycle design and optimization were performed with the goal of rigorous minimization of the steam consumption, i.e. focusing on minimization of the Operating Expenditures (OpEx) costs. However, the current model under-predicts the required steam consumption for the reported cyclic performance. Thus, the optimum SEWGS performance will shift towards somewhat increased steam consumptions. In order to already account for this in the current paper, the sensitivity of the efficiency and the SPECCA on the amount of rinse and purge steam are included and discussed in the result section as the steam required in the Rinse and the Purge essentially represents the energy penalty for CO_2 separation.

2.2. Economic assessment methodology and assumptions

The economic assessment is performed summing up the cost of the steel plant and the power generation section including MEA/SEWGS, CO_2 compression and auxiliary units. The cost of the steel plant was taken from the IEA report (Santos, 2019) and updated to 2017 values by TATA Steel consulting. The cost of the power generation section was determined using the bottom up approach as suggested by the European Benchmarking Task Force (EBTF) (Manzolini et al., 2015). The main assumptions made in this work are reported in Table 3.

The cost of the components in the power generation section is calculated based on their size and number, according to the following equation

$$C = n \cdot C_0 \cdot \left[\frac{S}{n \cdot S_0}\right]^f \quad (1)$$

where C_0 is the cost of a reference component with size S_0 and f is a scaling parameter. S is the actual size and n is the number of components. Equipment costs are summarized in Table 4.

Reference MEA costs were based on Wood in-house benchmark data, related to post-combustion CO_2 capture plants and adopting the scale factor reported in Table 4.

Both off-gases compressor and CO_2 compressor costs were set according to the values for similar equipment from other projects present in the Wood in-house database. Two off-gas compressors are considered (one operating and one spare), in order to have the highest availability consistently with the selection of the power plant configuration which includes two gas turbine combined cycles (GTCCs).

SEWGS plant cost assessment was performed assuming 5 identical SEWGS trains having a design life of 15 years.

The cost estimate was developed on the basis of Last Quarter 2018 cost level and in accordance with AACE International Cost Estimate Classification System which, due to the preliminary level of project definition, has an accuracy of +/- 30 % (AACE International

Table 1
Main thermodynamic assessment modelling assumptions.

Component	Unit	Value
Gas Turbine		
Turbine Inlet Temperature	°C	1270
Pressure ratio		18.1
Air flow rate (for base and reference cases)	kg/s	142
Heat Recovery Steam Cycle		
Condensing pressure	kPa	4.8
Condensing temperature	°C	32
HRSG HP/IP/LP boiler pressure	bar	130/28/4
HRSG HP/IP/LP boiler temperature	°C	331/230/144
SH and RH temperature	°C	565
ST HP/IP/LP adiabatic efficiency	%	92/94/88
Off-gases compressor		
N° of intercoolers		2
Polytropic efficiency	%	88.2
Pressure drop in heat exchangers	%	2-3
CO_2 capture section		
MEA heat duty	MJ/kg_{CO2}	3.03
Reboiler condensing temperature	°C	120
Absorber pressure losses	%	5
Fan isentropic efficiency	%	80
CO_2 compressor polytropic efficiency	%	85
CO_2 compressor specific work	kJ/kg_{CO2}	312

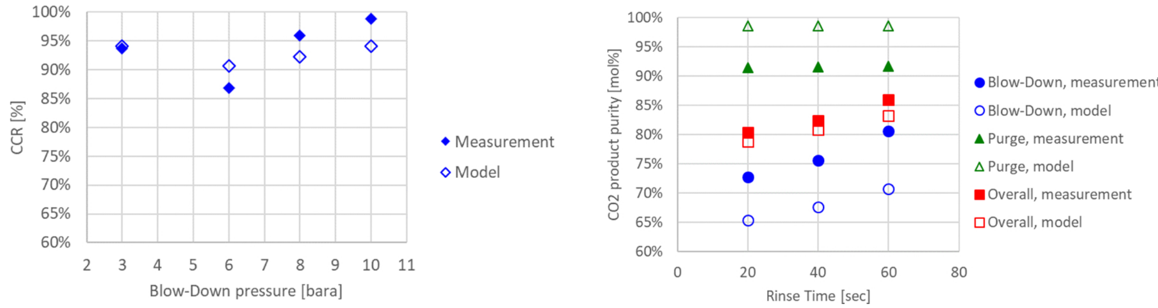

Fig. 3. Examples of measured and simulated carbon capture ratios (on the left) and CO_2 product purity (on the right) for the STEPWISE pilot operation.

Table 2
SEWGS performance modelling assumptions.

	Scenario A	Scenario B
CO_2 Capture Ratio	89.4 %	89.2 %
CO_2 purity	97.6 %	99.6 %
CO conversion	65 %	62 %
H_2 product temperature	440 °C	
CO_2 product temperature	440 °C	
S/C_{rinse}	0.1	
S/C_{purge}	0.4	
Rinse steam pressure and temperature	24 bar and 440 °C	
Purge steam pressure and temperature	1.5 bar and 440 °C	
N° of trains	5	
Height	12 m	

Table 3
Main economic assumptions and Steel plant section costs without power block (Manzolini et al., 2015).

Main economic assumptions	
Discount rate, %	8
Iron and steel plant operating hours	8600
Power generation section operating hours	8103
Steel Plant section	
Total Steel Plant Cost w/o power generation section, M€	4156
Total Fixed O&M, M€/y	371.5
Total Variable O&M, M€/y	939.9
Total Miscellaneous, M€	51.5
Total Other costs, M€	9.8
Total Revenues, M€	47.1

recommended Practice, 2018).

The procedure to determine Total Plant Costs (TPC) for the SEWGS section is described in the following:

1 The mechanical design of the SEWGS vessels was carried out considering a radial reactor configuration, developing a dedicated Finite Element Analysis model.
2 Direct material costs for reactors, reactor internals, heat exchangers and other main equipment have been estimated based on a specific, sized equipment list developed for the SEWGS plant. Cost data for critical items were requested and received from selected vendors, while other equipment material costs were obtained using Aspen Capital Cost Estimator or based on order values for similar equipment from other projects from the Wood in-house database.
3 The other components of the TPC have been estimated through factored cost parameters derived from the Wood in-house databases, together with a preliminary sizing of the main process lines and a preliminary plot layout. References for the use of Wood in-house database may be found in several techno-economic studies performed for IEAGHG reported in literature and relevant to several different CCS technologies (IEAGHG, 2018; IEAGHG, 2014; IEAGHG, 2008; IEAGHG, 2015).

Costs for the various sections of the SEWGS plant are reported in Table 5. These figures include 15 % contingency, which were considered in accordance with AACE recommended statistical ratio for Class IV Estimates (AACE International recommended Practice, 2018) and the White Paper "Toward a common method of cost estimation for CO2 capture and storage at fossil fuel power plants", produced collaboratively by authors from EPRI, IEAGHG, Carnegie Mellon University, MIT, IEA, GCCSI and Vattenfall (Rubin et al., 2013).

The above project contingency (15 %) was added on top of the technological contingency, which is included in the Equipment Costs and Total Plant Costs and was considered to determine the design conditions for the various process equipment. Adequate technological margins were adopted, accounting for the low maturity of the SEWGS technology, however those details are business confidential.

Starting from the bare equipment cost calculated as reported above, the installation costs, engineering, procurement and owner's costs are determined. Two different sets of coefficients using the EBTF bottom up approach have been adopted (Manzolini et al., 2015) and they are reported in Table 6. In particular, the coefficient for the CO_2 capture section were retrieved from a detailed economic assessment performed by Wood using an in-house methodology.

2.3. Key performance indicators

The application of CO_2 capture technologies to industry requires some discussion on the Key Performance Indicators (KPI) to be adopted

Table 4
Cost parameters for the power and capture sections (Chiesa and Macchi, 2004; Chiesa et al., 2005; Kreutz et al., 2005), updated using CEPCI index for 2017.

Plant component	Scaling parameter	Reference erected cost C_0 (M€)	Reference size S_0	Scale factor f	N°
GT, generator and auxiliaries	Net Power [MW]	49.4	272.12	0.45	2
HRSG, ducting and stack	U·S [MW/K]	32.6	12.9	0.67	1
ST, generator and auxiliaries	Gross Power [MW]	33.7	200	0.67	1
Cooling water system and BOP	Thermal power rejection [MW]	49.6	470	0.67	1
Expander	Expander Power [MW]	33.7	200	0.67	1
CO_2 compressor and condenser	Compression Power [MW]	44	50.5	0.67	1
Heat exchanger	Thermal power [MW]	6.1	828	0.67	–
MEA	CO_2 captured [kg/s]	67.9	53.7	0.8	1
Off-gases compressor	Power consumption [MW]	8.1	15.3	0.67	2

Table 5
SEWGS section costs (including contingency).

	Trains cost [k€]	N° of trains	Scale factor	Overall
Vessel costs	8880	5	1	44.4
WGS costs	550	5	1	3.1
Cooling section cost	2870	5	0.66	8.3
Installation and EPC costs	–	–	–	66.1
Total Plant Costs	–	–	–	121.9

and the parameter they refer to. The KPIs used in this work are listed below.

The specific primary energy consumption for CO_2 avoided (SPECCA) (Chiesa et al., 2011) is defined as the additional primary energy required (in GJ) to avoid the emission of 1 t of CO_2 producing the same amount of product (i.e. electricity or hot rolled coil):

$$SPECCA\left[\frac{GJ}{t_{CO2}}\right]=\frac{PEC_{capture}\left[\frac{GJ_{LHV}}{X}\right]-PEC_{nocapture}\left[\frac{GJ_{LHV}}{X}\right]}{E_{no\ capture\ SM}\left[\frac{t_{CO2}}{X}\right]-E_{capture\ SM}\left[\frac{t_{CO2}}{X}\right]} \tag{2}$$

where PEC is the Primary Energy Consumption, E is the specific CO_2 emission, capture and no-capture as subscripts refer to the two cases where the CO_2 capture is used and the base plant without CO_2 capture.

Another key performance indicator is the CO_2 Capture Ratio (CCR), defined as

$$CCR\,[\%]=\frac{E_{no\ capture\ SM}\left[\frac{t_{CO2}}{X}\right]-E_{capture\ SM}\left[\frac{t_{CO2}}{X}\right]}{E_{no\ capture\ SM}\left[\frac{t_{CO2}}{X}\right]}\times 100 \tag{3}$$

Ultimately, the Cost of CO_2 Avoided (CCA) is calculated as

$$CCA\left[\frac{€}{t_{CO2}}\right]=\frac{Cost_{capture}\left[\frac{€}{X}\right]-Cost_{nocapture}\left[\frac{€}{X}\right]}{E_{no\ capture\ SM}\left[\frac{t_{CO2}}{X}\right]-E_{capture\ SM}\left[\frac{t_{CO2}}{X}\right]} \tag{4}$$

where Cost stands for the cost of the primary product for the plant with and without capture, according to the subscripts no-capture and capture, respectively.

In detail, for an Iron and Steel plant, two functional units are defined taking the steel production and the net production of electricity into account. Thus, the SPECCA and the CCA can be calculated on electricity production base (X equal to MWh_{el}) or on hot rolled coil production (X equal to t_{HRC}), in order to have parameters consistent with both power and steel industries.

3. Investigated plant configurations

The most common integrated steel plant configuraton has a power generation section to cover the electricity demand for hot rolled coil (HRC) production exploiting the energy content of the steel making process off-gases. Table 7 details specifications of the gases feeding the power generation section. In general, compared to previous works (Santos, 2019; Gazzani et al., 2015), no natural gas addition is considered to the power generation section so that all the CO_2 emitted is related to the iron production process only. The integrated steel plant is connected to the electric grid which can balance the excess/deficit.

3.1. Base case definition

The first plant layout is shown in Fig. 4 and the characteristics of the main streams such as thermodynamic conditions and compositions as assessed with the GS code are reported in Table 8.

The power plant is based on two identical E-class gas turbines, each equipped with a heat recovery steam generator (HRSG) and a combined single steam turbine (ST). This plant configuration (2 + 2+1) was chosen to increase the availability and operational flexibility of the plant, though these cause penalties in terms of performance and costs. The HRSG is a three-pressure level and reheat type. The saturated steam produced in the Basic Oxygen Furnace (BOF) is introduced in the low-pressure drum of the heat recovery steam generator (HRSG). Gas turbine combined cycle (GTCC) assumptions are taken from the EBTF document (Gazzani et al., 2013b) to have consistent comparison with previous works (Gazzani et al., 2015; Sanchez Fernandez et al., 2014). The model was calibrated based on the performance and data of the above-mentioned E-class gas turbine (Gas Turbine World Handbook, 2010) and was adapted to use steel plant process gases as fuel. The main adaptation was the Turbine Inlet Temperature (TIT), which was lowered by 30 °C (in detail, 1270 °C vs. 1300 °C). As a term of comparison, current state-of-the-art large-scale gas turbines have a TIT up to around 1400 °C. Steel gases are cleaned before entering the intercooled compression unit (Santos, 2019), therefore no further abatement systems (i.e. Flue Gas Desulphurization) are required downstream of the HRSG.

Compared to a previous work (Gazzani et al., 2015), this base case configuration is different as it adopts two small gas turbines with lower TIT and the off-gases composition is slightly different being specific to the pilot plant site.

3.2. Reference case definition

The reference plant for CO_2 capture in a steel plant is based on the combined cycle previously discussed and a post-combustion capture section with standard monoethanolamine (MEA) solvent in the scrubbing section. A schematic layout is shown in Fig. 5.

Because of the high CO_2 intensity of the blast furnace gases, the amount of heat available for solvent regeneration is the limiting aspect for the CO_2 capture ratio. Thus, a back-pressure steam turbine is selected in order to achieve the highest CO_2 capture ratio while keeping a good thermodynamic efficiency. The capture plant is designed to use all the heat available from the condenser of the steam turbine to capture CO_2 from the flue gas. The saturated steam produced by the BOF is mixed with the steam taken from the heat recovery steam cycle (HRSC) and used for MEA regeneration. With a CO_2 capture ratio in the range of 45 %, it is assumed that the exhaust gas of only one HRSG is sent to the

Table 6
Methodology and coefficient adopted for the calculation of the Total Plant costs starting from the equipment ones (Manzolini et al., 2015).

Direct costs as percentage of the total equipment costs (TEC)	Power generation section	CO_2 capture section	
Piping/valves, Civil Works, Instrumentation, steel-structure, Erection, etc.	66 %	104 %	X% TEC
Total Installation Costs [TIC]	66 %	104 %	Y% TEC
TOTAL DIRECT PLANT COSTS [TDPC]		**TEC + TIC**	
Indirect costs [IC]	14 %	14 %	14 % TDPC
Engineering Procurement and Construction [EPC]		**TDCP + IC**	
Contingency [Co]	10 %	10 %	10 % EPC
Owner's cost [OC]	5 %	5 %	5 %EPC
TOTAL CONTINGENCIES&OC [Co&OC]	15 %	15 %	15 % EPC
TOTAL PLANT COST [TPC]		**EPC + C&OC**	

Table 7
Specifications of flue gases available in steel plant.

	T	p	m	LHV	composition %mol								CO_2 intensity
	°C	bar	kg/s	MJ/kg	CH_4	CO	CO_2	C_2H_6	H_2	H_2O	N_2	O_2	g_{CO2}/kWh_{LHV}
BOFG	50	1.11	14.2	5.9	0.0	56.9	14.4	0.0	2.4	12.2	13.8	0.0	675
BFG	25	1.11	158.7	2.4	0.0	22.3	22.1	0.0	3.6	3.2	48.8	0.0	978
COG	30	1.11	0.3	40.0	23.0	3.8	0.96	2.7	59.5	4.0	5.8	0.2	139
Overall	30	1.11	173.1	2.7	0.1	25.3	21.4	0.0	3.8	3.6	45.7	0.0	907

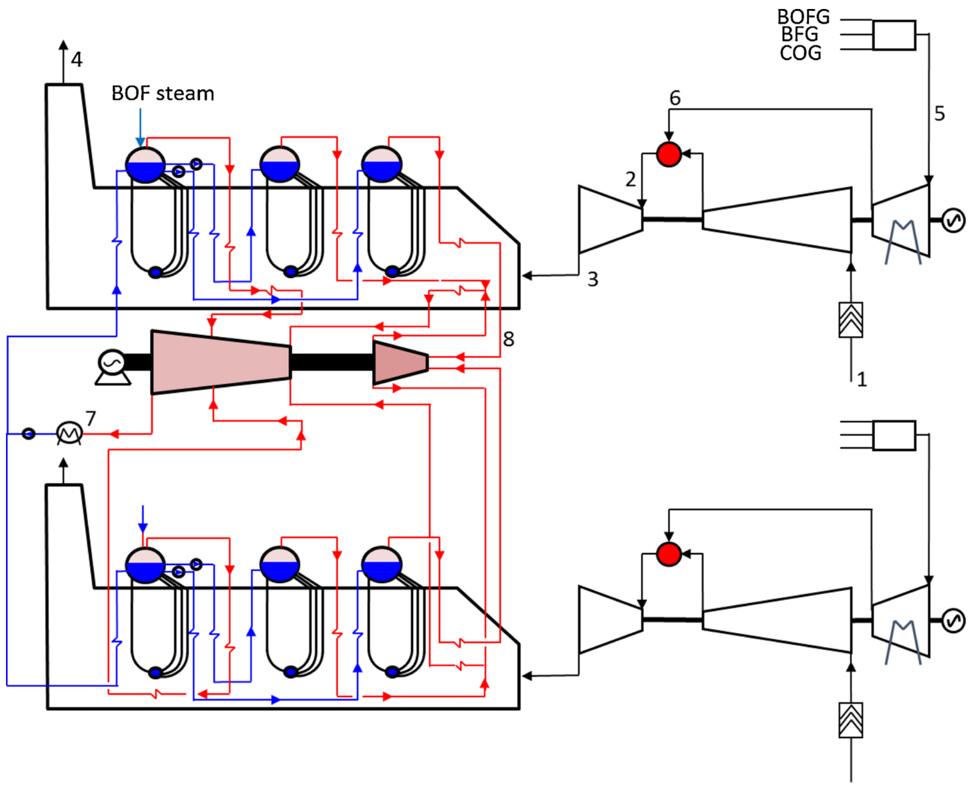

Fig. 4. Schematic layout of the considered GTCC named the base case.

Table 8
Thermodynamic conditions, flow rates and compositions of the main streams in Fig. 3. The flow rates with an asterisk (*) refer to one gas turbine and one HRSG.

	T	p	m	LHV	Molar composition (%)									
point	°C	bar	kg/s	MJ/kg	Ar	CH_4	CO	CO_2	C_2H_6	H_2	$H_2O_{(V)}$	N_2	O_2	$H_2O_{(L)}$
1	15	1.01	142.0*		0.9						1.0	77.3	20.7	
2	1389	17.6	175.5*		0.5			24.5			2.9	68.0	4.1	
3	602	1.01	226.8*		0.6			18.5			2.4	70.3	8.1	
4	86	1.01	226.8*		0.6			18.5			2.4	70.3	8.1	
5	30	1.11	86.6*	2.7		0.1	25.3	21.4	0.01	3.8	3.6	45.7		0.1
6	112	27	84.8*	2.8		0.1	25.7	21.7	0.01	3.9	2.1	46.4		
7	32	0.05	68.2								100.0			
8	560	120.9	50.0								100.0			

capture section, while the other is sent directly to the stack in order to reduce costs and auxiliary consumptions.

As shown in Fig. 5, the flue gas sent to the CO_2 capture section is initially pre-treated in a direct contact cooler to reach a suitable temperature at the absorber, where CO_2 separation from the flue gas occurs. The solvent is thermally regenerated in the stripper using the steam condensation heat. The CO_2 product gas, once separated from the condensate, is compressed, liquefied and pumped to 110 bar as set by pipeline requirements.

The characteristics of the main streams such as thermodynamic conditions and compositions as assessed with the GS code are reported in Table 9.

3.3. SEWGS integration in steel-plant

Different levels of SEWGS integration in the iron steel plant can be considered, but the simplest consists of decarbonizing the power generation section fuel featuring a CO_2 capture pre-combustion lay-out. In this configuration, the maximum emission reduction for the integrated steel plant is lower than 50 %. A more complex configuration including

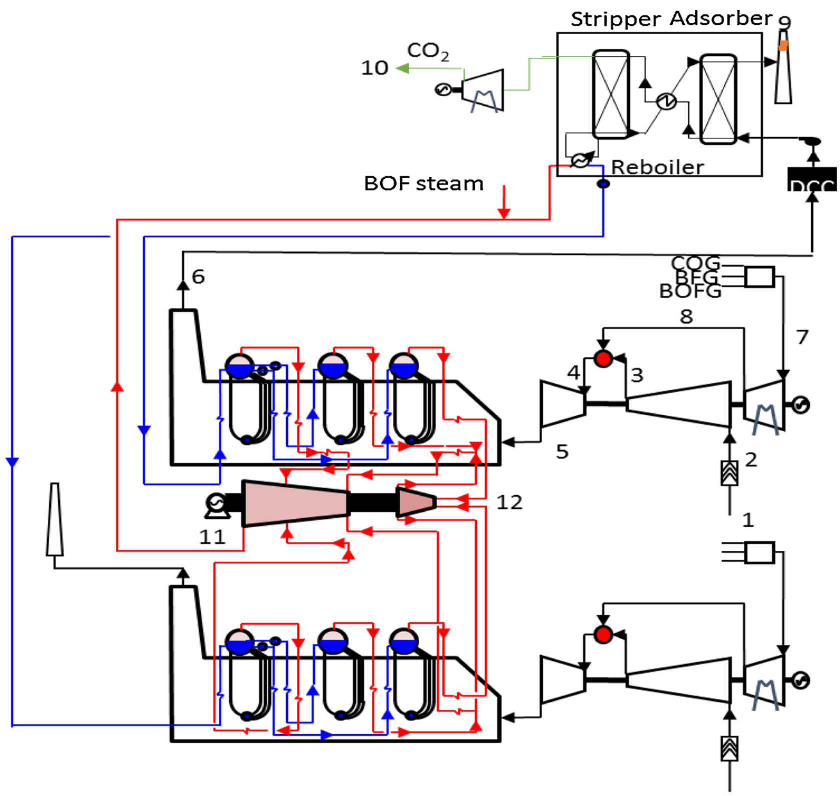

Fig. 5. Schematic layout of the considered GTCC with post-combustion MEA capture named reference case.

Table 9
Thermodynamic conditions, flow rates and compositions of the main streams in Fig. 5. The flow rates with an asterisk (*) refer to one gas turbine and one HRSG.

point	T	p	m	LHV	Molar composition (%)									
	°C	bar	kg/s	MJ/kg	Ar	CH_4	CO	CO_2	C_2H_6	H_2	$H_2O_{(V)}$	N_2	O_2	$H_2O_{(L)}$
1	15	1.01	142.0*		0.9						1.0	77.3	20.7	
2	15	1	142.0*		0.9						1.0	77.3	20.7	
3	430	18.16	118.4*		0.9						1.0	77.3	20.7	
4	1389	17.61	175.5*		0.5			24.5			2.9	68.0	4.1	
5	602	1.01	226.8*		0.6			18.5			2.4	70.3	8.1	
6	159	1.01	226.8*		0.6			18.5			2.4	70.3	8.1	
7	30	1.11	86.6*	2.7		0.1	25.3	21.4	0.01	3.8	3.6	45.7		0.1
8	112	27	84.8*	2.8		0.1	25.7	21.7	0.01	3.9	2.1	46.4		
9	55	1.01	200.0		0.7			11.1			2.7	76.7	8.9	
10	30	110	53.7					100.0						
11	130	2.7	65.9								100.0			
12	562	120.9	50.1								100.0			

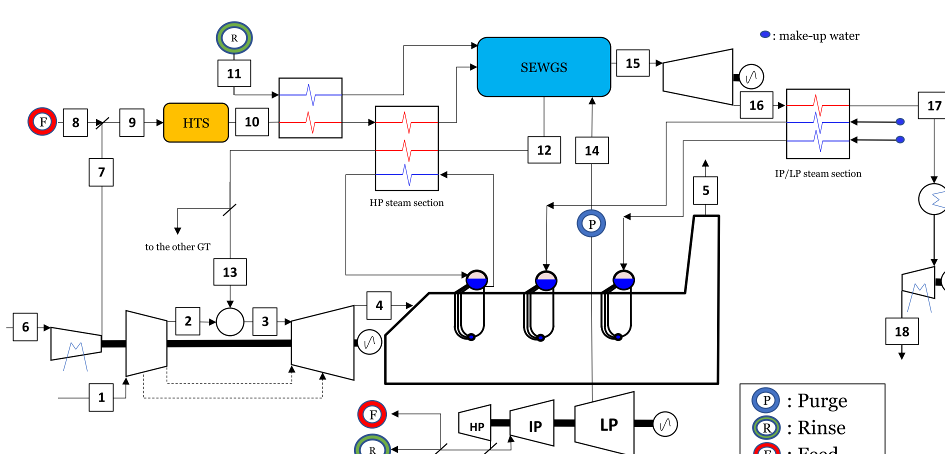

Fig. 6. Schematic layout of the SEWGS configuration with expander (only one GT unit is represented for the sake of simplicity).

exhaust gas recycling must be considered in order to increase the steel plant emission reduction up to 85 %. This configuration was assessed as part of this study, though the SEWGS operating conditions would be significantly different from the tested ones.

In detail, this work focuses on the simplest approach, which was demonstrated at the STEPWISE pilot plant in Luleå (Sweden). Two different lay-outs are proposed here: a first one where the CO_2 separated in the SEWGS is expanded below atmospheric pressure (namely Expander lay-out and abbreviated as EXP in the following) to exploit the steam energy content and a second (namely Saturator lay-out and abbreviated as SAT in the following) where a fraction of the steam necessary for the Water Gas Shift is provided by a saturator. Both cases require an off-gas intercooled compressor, but with higher pressure ratio to overcome the additional pressure losses. These two configuration cases are described in the following.

3.3.1. Expander lay-out

The first plant configuration exploiting the SEWGS technology is schematically reported in Fig. 6. The characteristics of the main streams such as thermodynamic conditions and compositions as assessed with the GS code, referring to scenario A in Table 2, are reported in Table 10.

After compression (7), the BOFG, COG and BFG are mixed with steam (8) bled from the outlet of the HP turbine section and then sent to a High Temperature Shift (HTS) reactor to convert CO into CO_2 and transferring its energy content to H_2. The discharge pressure of the intercooled compressor is duly set to 25 bar to compensate pressure losses occurring in the remaining downstream components. Moreover, the last stage of the intercooled compressor is designed to match the HTS inlet temperature (320 °C), resulting in a higher power consumption.

After the HTS section, the syngas is cooled to 400 °C to be fed to the SEWGS reactor, operating at 24 bar. Here, CO_2 adsorption and WGS reaction take place, leading to very high CO conversion. The H_2 product (12) leaves the SEWGS reactor and is sent to the gas turbine. However, the H_2 product needs to be preliminarily cooled down to 350 °C before fueling the GT unit (Manzolini et al., 2011). Thus, a waste-heat boiler is adopted to produce additional HP steam (at 330.8 °C and 130 bar) for the HRSC.

On the other side, the CO_2 product (15) enters the expander and is next cooled down to 105 °C in the IP/LP steam section. Then it enters the CO_2 condenser (as stream 17), where the water is removed, and finally is compressed in the CO_2 compression unit. During CO_2 compression, the remaining steam is removed with a series of adiabatic flash units placed between two consecutive stages and a dehydration step. In this configuration, the purge steam required for the SEWGS cycle is taken from the LP super-heater of the HRSC while the rinse steam required for the SEWGS cycle is taken in the same way from the exit of the HP steam turbine.

The presence of the expander has two significant impacts on this power plant configuration: (i) the expander provides additional power to the overall plant, but (ii) the specific compression work of the CO_2 compressor is higher as a consequence of the sub-atmospheric CO_2 pressure at the compression unit inlet. Therefore, the choice of the discharge pressure has been optimized accounting for the specific compression work. A preliminary analysis showed that the optimal expander pressure ratio is equal to 2.5 (1.25 and 0.5 bar as inlet and outlet pressures, respectively): this value has been assumed for the performance assessment.

3.3.2. Saturator lay-out

The plant configuration schematically shown in Fig. 7 reports that the steam for the WGS section is partly provided by a saturator and partly by steam bleeding from the turbine.

The advantage of the saturator consists of recovering low grade heat by maximizing the steam content of the steel mill off-gases before they are mixed with the H_2O feed coming from the steam turbine. In fact, the steam for the HTS process accounts for one of the largest efficiency losses of the power plant. The saturator is a direct contact heat exchanger, where liquid water is introduced at around 200 °C from the top to the bottom, while the syngas enters the bottom and is gradually saturated with steam. As a drawback, the use of a saturator implies a considerable amount of heat exchange for water recirculation and regeneration.

A difference of this configuration compared to the one in Fig. 6 is the selection of a three-stage intercooled compressor, resulting in lower power consumption: the syngas compression temperature is decoupled from the HTS inlet temperature requirements. After the intercooled compression, the relatively hot syngas (7) is cooled down and then it enters the saturator at around 130 °C, from which it comes out saturated with water (8). When the syngas exits the saturator, it undergoes a series of heat exchange stages to reach the required temperature of 320 °C for the HTS, followed by gas cooling before entering the SEWGS section. The H_2 product stream (13) is cooled down to 350 °C to meet combustion chamber inlet conditions requirements in the dedicated HP steam section, similarly to the Expander case configuration in Fig. 6. The CO_2 products exiting the SEWGS unit (16) are cooled down producing IP and LP steam without any expander. In this case, more IP steam can be produced as there is no longer a temperature drop due to

Table 10

Thermodynamic conditions, flow rates and compositions of the main streams in Fig. 6. The flow rates with an asterisk (*) refer to one gas turbine and one HRSG.

point	T °C	p bar	m kg/s	LHV MJ/kg	Molar composition (%) Ar	CH_4	CO	CO_2	C_2H_6	H_2	H_2O	N_2	O_2	$H_2O_{(L)}$
1	15	1.01	169.0*		0.9			0.0			1.0	77.3	20.7	
2	433	18.16	131.6*		0.9			0.0			1.0	77.3	20.7	
3	1337	17.61	175.7*		0.7			2.2			14.0	75.0	8.1	
4	559	1.04	213.0*		0.7			1.9			11.9	75.4	10.2	
5	80	1.01	213.0*		0.7			1.9			11.9	75.4	10.2	
6	30	1.11	173.1	2.7		0.1	25.3	21.4	0.01	3.8	3.6	45.7		0.1
7	340	25.0	171.4	2.8		0.1	25.8	21.8	0.01	3.9	2.0	46.5		
8	301	25.0	37.4								100.0			
9	320	25.0	208.6	2.2		0.1	18.9	15.9	0.01	2.8	28.3	34.0		
10	464	24.5	208.6	2.0		0.1	5.1	29.7	0.01	16.6	14.6	34.0		
11	301	25.0	4.8								100.0			
12	440	24	88.0	4.7		0.1	2.1	4.0	0.01	34.8	2.4	56.5		
13	350	23.2	44.0*	4.7		0.1	2.1	4.0	0.01	34.8	2.4	56.5		
14	440	1.5	19.4								100.0			
15	440	1.5	144.9					53.3			45.4	1.3		
16	326	0.5	144.9					53.3			45.4	1.3		
17	105	0.5	144.9					53.3			45.4	1.3		
18	30	110	107.8					97.6				2.4		

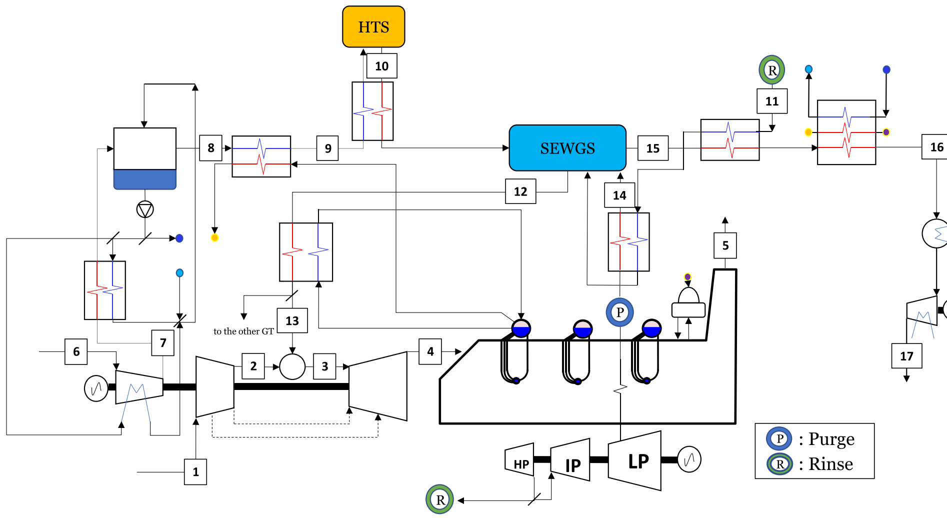

Fig. 7. Schematic layout of the SEWGS configuration with saturator (only one GT unit is represented for the sake of simplicity).

absence of an expander.

The characteristics of the main streams such as thermodynamic conditions and compositions as assessed with the GS code and referring to scenario A (see Table 2) are reported in Table 11 according to the numbering in Fig. 7.

4. Performance results

In the previous section, along with the description of the plant lay-outs, preliminary results related to thermodynamic conditions, flow rates and compositions of the most relevant streams have been presented. Table 12 summarizes the power balances for the two lay-outs of plants exploiting the SEWGS technology, according to the two scenarios reported in Table 2, together with the performance of the base and reference cases.

The overall net power output of the gas turbine is quite similar for all the cases. Slight differences for the SEWGS cases can be prescribed to small variation in the fuel gas composition at the GT combustor inlet.

The steam cycle power output for the SEWGS cases is reduced compared to the base case and varies because of the different strategies adopted to provide the steam for the WGS reaction (the amount of steam for the purge and rinse steps is the same between all cases). Indeed, the SAT cases have a higher power output in line with the lower amount of steam bled from the HRSC. Although the steam turbine power output for the SEWGS cases is lower than the base case by 40 %, for the SAT cases, it is higher than the reference case based on MEA.

Different CO_2 compression power consumptions can be noted due to the specific SEWGS case and scenario. The EXP case is more demanding than the SAT case as consequence of the lower pressure at the CO_2 compression station inlet. Between the two scenarios, case B must be preferred as it guarantees a higher CO_2 purity with benefit for the CO_2 compression work (accounted here), but also in terms of transportation cost and issues (not accounted here).

Moving to the FG_{LHV} compressor, the power consumption varies from case to case as the pressure ratio at the intercooled compression stages is tuned to satisfy the operating specifications of the power plants under comparison. In general, the pre-combustion section (WGS, SEWGS and heat exchangers) introduces additional pressure losses compared to the base and reference cases causing higher compression work. Between the two SEWGS cases, the FG_{LHV} temperature at the compressor outlet for the EXP cases is higher compared to the SAT cases, as anticipated in Tables 10 and 11 justifying the power consumption difference of 4 MW.

The expander adopted in the lay-out of Fig. 6 generates around 20 MW, on the other hand, the SAT lay-out takes advantage of the limited steam extraction for the WGS. From an overall perspective,

Table 11
Thermodynamic conditions, flow rates and compositions of the main streams in Fig. 7. The flow rates with an asterisk (*) refer to one gas turbine and one HRSG.

	T	p	m	LHV	Molar composition (%)									
point	°C	bar	kg/s	MJ/kg	Ar	CH_4	CO	CO_2	C_2H_6	H_2	H_2O	N_2	O_2	$H_2O_{(L)}$
1	15	1.01	169.0*		0.9			0.0			1.0	77.3	20.7	
2	433	18.16	131.6*		0.9			0.0			1.0	77.3	20.7	
3	1337	17.61	175.7*		0.7			2.2			14.0	75.0	8.1	
4	559	1.04	213.0*		0.7			1.9			11.9	75.4	10.2	
5	80	1.01	213.0*		0.7			1.9			11.9	75.4	10.2	
6	30	1.11	173.1	2.7		0.1	25.3	21.4	0.01	3.8	3.6	45.7		0.1
7	225	27.0	170.2	2.8		0.1	26.1	22.0	0.01	3.9	0.9	47.0		
8	167	26.2	208.6	2.2		0.1	18.9	15.9	0.01	2.8	28.3	34.0		
9	252	25.67	208.6	2.2		0.1	18.9	15.9	0.01	2.8	28.3	34.0		
10	464	24.5	208.6	2.0		0.1	5.1	29.7	0.01	16.6	14.6	34.0		
11	301	25.0	4.8								100.0			
12	440	24.0	88.0	4.7		0.1	2.1	4.0	0.01	34.8	2.4	56.5		
13	350	23.2	44.0*	4.7		0.1	2.1	4.0	0.01	34.8	2.4	56.5		
14	440	1.5	19.4								100.0			
15	440	1.5	144.9					53.3			45.4	1.3		
16	120	1.5	144.9					53.3			45.4	1.3		
17	30	110	107.8					97.6				2.4		

Table 12
Energy performance of the SEWGS cases vs. base and reference cases.

	Base Case	Ref case	EXP, A	SAT, A	EXP, B	SAT, B
GT, Net power [MW]	99.6	99.6	98.3	98.2	98.6	98.5
SC, Net power [MW]	95.1	55.8	53.1	58.8	53.1	58.9
CO_2 compression [MW]		18.3	43.6	32.3	43.0	31.9
FG_{LHV} compressor [MW]	59.8	59.8	74.1	70.1	74.1	70.1
Expander [MW]			21.5		21.3	
B.O.P. [MW]	1.3	1.3	1.3	1.3	1.3	1.3
Net power, total [MW]	233.2	175.6	152.2	151.5	153.4	152.7
FG thermal input [MW]	471.5	471.5	471.5	471.5	471.5	471.5
Net electric LHV efficiency [%]	49.45	37.24	32.29	32.14	32.53	32.39
Power plant specific CO_2 emissions [kg/MWh]	1835	1337	308.1	315.8	312.0	307.1
CCR_{PP} [%]		27.1	83.2	82.8	83.0	83.3
$SPECCA_{PP}$ [MJ/kg_{CO2}]		4.80	2.54	2.58	2.49	2.51
Coal PEC [MJ/t_{HRC}]	21.32	21.32	21.32	21.32	21.32	21.32
Coking Primary Energy value	−0.9	−0.9	−0.9	−0.9	−0.9	−0.9
Steel plant specific CO_2 emissions [kg/t_{HRC}]	1112	1112	1112	1112	1112	1112
Average Electricity balance [MW]	−33.0	20.3	41.9	42.5	40.8	41.5
CO_2 debit for electricity import [kg/s]	−4.2	2.6	5.3	5.4	5.2	5.3
Total specific CO_2 emissions [kg/t_{HRC}]	2016	1647	1257	1260	1258	1257
CCR_{SM} [%]		18.3	37.6	37.5	37.6	37.7
$SPECCA_{SM}$ [MJ/kg_{CO2}]		2.46	1.95	1.97	1.92	1.93

limited differences in the net power output between the four SEWGS cases can be pointed out (± 1 MW).

The net power output is slightly higher than 150 MW, which is significantly lower compared to the base case, but also to the reference case. This result shows a clear impact on the electric efficiency which reduces by 17 % and 5 % points with respect to the base and reference cases, respectively. However, considering the carbon capture ratio and focusing on the power generation section only, the SEWGS technology can reduce CO_2 emissions by more than 80 % with SPECCA values as low as 2.5 MJ/kg_{CO2}. This result is interesting since it is significantly lower than the SPECCA of 4.8 MJ/kg_{CO2} for the reference case with only 27 % of CO_2 avoidance.

When considering the entire steel plant, the introduction of capture technologies affects only the electricity import as consequence of the lower plant power output: the electricity import (positive) for the MEA case is around 20 MW_{el}, while for the SEWGS ones it is more than 40 MW_{el}. These numbers account for the different availability between the power generation section and iron and steel plant. The electricity purchase from the grid brings about additional CO_2 emissions related to the electricity generation in the power stations assuming a European average generation park.

In general, the higher CCR of SEWGS is transferred to the entire plant achieving a lower CO_2 specific emissions together with lower SPECCA.

Results actually depend on a number of assumptions as reported in Table 2, with particular reference to the S/C values for both purge and rinse. Here, in order to investigate the response of the plant at S/C variations, the results of a parametric analysis in terms of the two most relevant figures of merit, i.e. LHV efficiency and SPECCA are reported in Fig. 8, specifically referring to the SAT case and scenario B for brevity. As expected, the higher the S/C for both purge and rinse, the lower the efficiency and the higher the SPECCA. The trend is the same when referring to the plant lay-out with the expander, but in this case it should be considered that less steam is present in the heat recovery steam cycle, so the upper values of S/C included in the trends of Fig. 8 may be unfeasible.

The sensitivity shows that even in the worst-case scenario, the SPECCA related to the SEWGS technology is about 3.3 MJ/kg_{CO2} which is still lower than the reference case. Future cycle optimization based on progressive model developments and validations are foreseen to further detail the system performance within this illustrated selectivity window.

Moving to the economic assessment, results are summarized in Table 13. The base case has costs of electricity and HRC equal to 69 €/MWh_{el} and 468 €/t_{HRC} which increase to 112 €/MWh_{el} and 482 €/t_{HRC} for the reference case. The higher costs of the reference case are mainly related to the MEA and CO_2 compressor capital cost and the lower power output which results, in the case of the integrated plant, in 29 M€/y additional electricity cost.

The SEWGS cases have even higher cost of electricity and cost of HRC, in the range of 150–157 €/MWh_{el} and 493–495 €/t_{HRC} respectively, as consequence of the higher CO_2 avoided which brings about additional capital costs for the compressor, no steam turbine cost reduction (as it was for the reference case) and a significant lower power

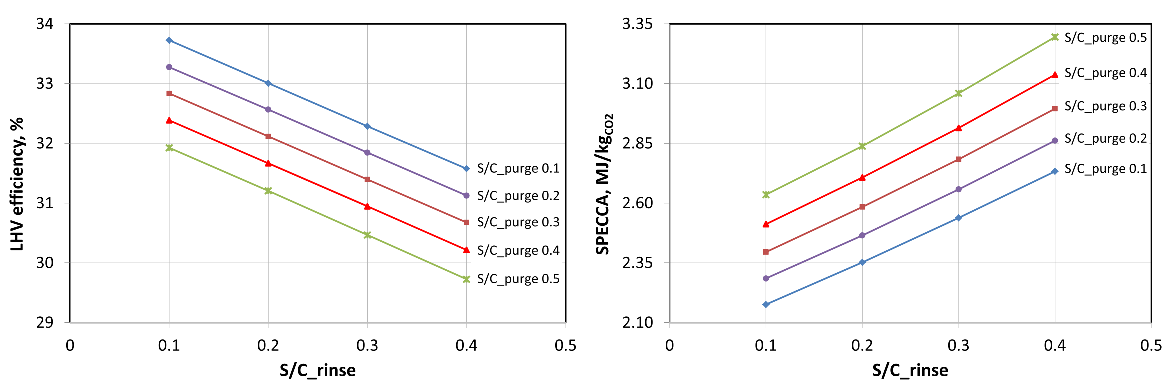

Fig. 8. LHV efficiency (left side) and SPECCA (right side) of the power plant adopting a saturator as a function of different S/C values for rinse and purge (calculation assumptions refer to scenario B).

Table 13
Economic assessment of the SEWGS cases vs. base and reference cases.

	Base Case	Ref case	EXP, A	SAT, A	EXP, B	SAT, B
POWER GENERATION SECTION ONLY						
Gas Turbine [M€]	61.3	61.3	61.0	61.0	61.1	61.0
HRSC [M€]	60.2	30.5	57.1	58.2	57.1	58.2
Off-Gases Compressor [M€]	39.4	39.4	45.5	43.8	45.5	43.8
SEWGS [M€]			47.5	47.5	47.5	47.5
MEA [M€]		66.3				
Expander [M€]			7.4		7.3	
SEWGS Heat Exchangers [M€]	0.2	0.6	8.3	7.5	8.3	7.5
CO_2 compression [M€]		21.7	38.9	31.8	38.5	31.5
BOP [M€]		0.2	0.2	2.4	0.2	2.4
Total equipment cost [M€]	161.1	220.0	265.8	252.2	265.3	252.0
Total installation costs [M€]	109.6	183.2	211.8	200.0	211.6	200.7
TDPC [M€]	270.7	403.1	477.6	452.2	476.9	452.7
Indirect, owner and contingencies [M€]	84.2	125.4	158.0	150.1	157.8	150.2
Sorbent [M€]			63.0	63.0	63.0	63.0
Total plant cost [M€]	354.9	528.5	698.6	665.4	697.7	665.9
Fixed costs [M€/y]	17.4	24.4	32.5	31.2	32.4	31.2
Variable costs [M€/y]	2.3	3.9	13.1	13.1	13.1	13.1
LCOE [€/MWh_{el}]	69.0	111.9	163.4	157.7	162.0	158.9
Cost of CO_2 avoided [€/t_{CO2}]	–	86.4	61.9	58.4	61.1	58.9
INTEGRATED STEEL PLANT						
Steel mill Cost (with PP) [M€]	4511	4685	4852	4825	4851	4824
Electricity cost [M€/y]	−17.4	11.3	24.8	24.1	24.2	24.6
Steel mill yearly cost (with PP) [M€/y]	545	564	583	579	583	579
Fixed O&M_{SM} [M€/y]	1345	1354	1371	1370	1371	1370
C_{HRC} [€/t_{HRC}]	468	482	495	493	494	493
CCA_{SM} [€/t_{CO2}]	–	38.2	34.9	33.1	34.7	33.2

output. Comparing the equipment cost of the capture sections only, the SEWGS and heat exchangers are cheaper than MEA, however, other components as the HRSC and the off-gas compressor are more expensive leading to a higher overall equipment cost.

In addition, the sorbent cost is certainly relevant as it has to be accounted for both in the capital cost and in the variable costs (+9.2 M €/y compared to the reference case).

However, the resulting cost of CO_2 avoided which is the correct parameter to be used to compare different CO_2 capture technology is lower for SEWGS than for the reference case by around 15 % from both power plant and steel plant perspectives: this is because the additional CO_2 avoided more than balance the higher LCOE and cost of HRC (see Eq.(4)). The SEWGS configuration doubles the CO2 avoided compared to the reference case.

Comparing the different SEWGS configurations, limited differences can be noted (below 2 €/t_{CO2} which corresponds to less than 8 % difference) and considering also the accuracy of the economic assessment, no final considerations can be drawn.

The impact of the SEWGS performance (i.e. rinse and purge steam usage) on the economic results is performed, and results are reported in Fig. 9 (only SAT,B is reported for brevity). For any of the SEWGS consumptions considered, the cost of CO_2 avoided for both the power generation section and integrated steel plant are lower than the ones of the reference technology. Finally, a limited variation of the cost of CO_2 avoided for the entire steel plant (± 1.5€/t_{CO2}) can be noted as the capture section accounts for only 50 % of the overall plant emissions and even less cost share.

5. Conclusions

This work discusses the preliminary economic assessment of SEWGS when integrated with a steel works. The analysis was focused on SEWGS cycle performance and determined the final CO_2 capture ratio and additional costs compared to not implementing CO_2 capture and a comparison to using state of the art capture technology.

A simplified lay-out consisting of using the SEWGS to separate the CO_2 from the flue gases with energy content was proposed. The system performance and costs were determined on using preliminary SEWGS cycle performance and capital cost.

Detailed mass and energy balances showed the potential of SEWGS to reduce CO_2 emissions with Specific Energy Consumptions for CO_2 Avoided (SPECCA) around 2.5 MJ/kg_{CO2}, which is significantly lower

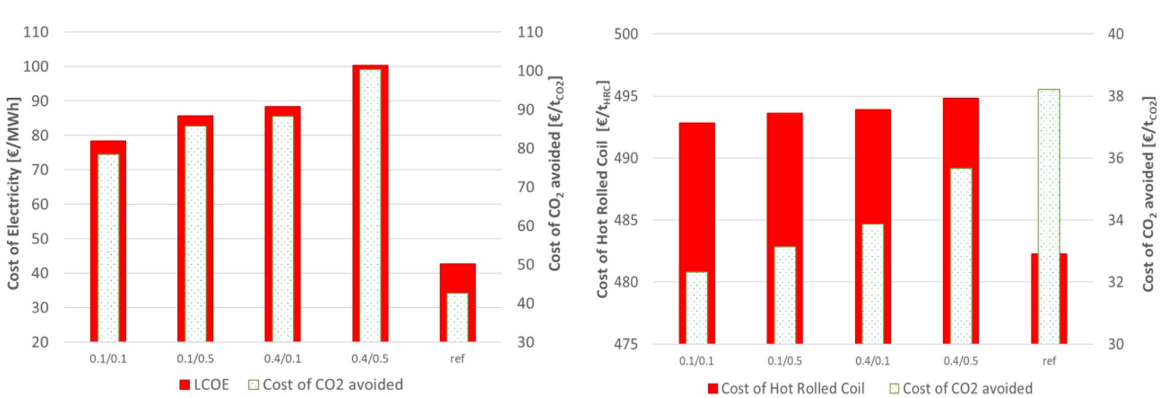

Fig. 9. Sensitivity analysis on the economic assessment for the Saturator lay-out (scenario B) assuming different S/C values for the rinse and purge (In the picture the first number refers to the rinse and the second to the purge).

than 4.8 MJ/kg_{CO2} achieved by amine scrubbing technology (these numbers refer only to the power generation section of the steel plant). When considering the entire steel plant, the SPECCA is below 2 MJ/t_{CO2} confirming the limited penalties related to the CO_2 capture introduced by the SEWGS.

The cost of hot rolled coil increases from 468 €/t_{HRC} in the base case to 493 €/t_{HRC} when SEWGS is considered with a cost of CO_2 avoidance of 33 €/t_{CO2}.

The sensitivity of the efficiency and SPECCA towards the steam consumption in the rinse and purge of the SEWGS technology shows that even with substantially increased steam consumption the technology outperforms the reference scenario from both energy and economic perspective. Future works will develop an integrated optimization between the SEWGS process modelling and the steel plant techno-economic assessment.

CRediT authorship contribution statement

G. Manzolini: Conceptualization, Methodology, Investigation, Writing - original draft. **A. Giuffrida:** Methodology, Software, Investigation, Writing - review & editing. **P.D. Cobden:** Writing - review & editing, Funding acquisition. **H.A.J. van Dijk:** Writing - review & editing, Funding acquisition, Formal analysis. **F. Ruggeri:** Software. **F. Consonni:** Software, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper is part of the STEPWISE project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 640769.

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