16th International Conference on Greenhouse Gas Control Technologies, GHGT-16

23rd -27th October 2022, Lyon, France

SEWGS integration in a DR-process

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Abstract

The iron and steel industry represents one of the most carbon intensive sector accounting for roughly 25% of CO_2 emissions from the industrial sectors and 7% of total energy sector emissions. The aim of this work is to assess the techno-economic analysis of the integration of the SEWGS technology in the DRI/EAF process in order to reduce the carbon footprint of this steelmaking process. The analysis has been carried out taking real plant data from literature, and investigating possibilities of GHG mitigation by introducing carbon-capture technologies such as MDEA scrubbing or the SEWGS technology. The solution with the SEWGS technology integrated shows environmental and economic advantages with respect to the case in which the MDEA carbon capture section is adopted. A reduction of emissions near 90%, with respect to the BF/BOF route, can be reached with the implementation of SEWGS when a renewable electricity scenario is considered. In addition, the CCA of this solution, always in comparison with the BF/BOF route, is quite similar to the one of the base DRI/EAF plant. The integration of SEWGS technology thus represents a promising solution for the reduction of the carbon footprint of the DRI/EAF process and commercially viable in the near future considering that the DRI/EAF process is already globally commercialized.

Keywords: steel industry; Direct Reduced Iron; SEWGS; CO_2 mitigation; MDEA; carbon capture

1. Introduction

In the pathway towards an economy with net zero GHG emissions, the decarbonization of the industrial sector represents one of the main challenges for the next decades. The steelmaking industry is one of the most energy and carbon intensive relying on the use of fossil fuels. Indeed, in 2019 the iron and steel sector globally accounted for 845 Mtoe of energy consumption, representing 20% of industrial energy use and 8% of total final energy use [1]. In addition, the sector, in the same period, accounted for 2.6 Gt of direct carbon dioxide emissions, representing roughly 25% of CO_2 emissions from the industrial sectors and 7% of total energy sector emissions [1]. Different routes can be used to produce steel. More than 80% of steel is globally produced via primary routes from iron ore and some scrap while the rest is manufactured via recycled scarp. The blast-furnace and basic-oxygen-furnace route (BF-BOF) route represents the 70% of global steel production and around 90% of primary production [1]. The remainder 10% of primary steel production is accounted to direct reduced iron-electric arc furnace route (DRI-EAF) [1]. BF-BOF and

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EAF (DRI-EAF and scrap-based EAF) routes represent the 95% of total steel produced [1]. In light of the data shown above becomes crucial the decarbonization of the steelmaking sector.

In this paper the techno-economic assessment of the integration of the Sorption Enhanced Water Gas Shift (SEWGS) in the production of direct reduced iron is performed. The integration of the SEWGS allows the removal of carbon dioxide from the gas stream that leaves the top of the shaft furnace. In the shaft furnace iron ore is reduced by carbon monoxide and hydrogen that are produced via methane reforming, generating direct reduced iron at the bottom of the shaft. In addition to the CO_2 stream that can be compressed and stored, SEWGS also produces a H_2-rich stream that can be used as fuel in the reformer thus generating CO_2-free flue gases (Fig 3). The integration of the SEWGS in the DR process has therefore the strong potential to reduce the carbon emissions of this process.

Nomenclature

BF	Blast Furnace
BOF	Basic Oxygen Furnace
CCA	Cost of CO_2 avoided [€/t_{CO2}]
CCS	Carbon Capture and Storage
CI	Carbon Intensity
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
GHG	Greenhouse Gases
HRC	Hot Rolled Coil
LCOHRC	Levelized Cost Of Hot Rolled Coil
MDEA	Methyldiethanolamine
NG	Natural Gas
PEC	Primary Energy Consumption [GJ/$t_{product}$]
SEWGS	Sorption Enhanced Water Gas Shift
SPECCA	Specific Primary Energy Consumption for CO_2 Avoided
TEC	Total Equipment Cost [€]
TPC	Total Plant Cost [€]
WGS	Water Gas Shift

1.1. The DRI-EAF process

The DRI-EAF process represents an alternative primary steel production route to the traditional BF/BOF route [1]. Solid primary iron (DRI) is produced from iron ores through reducing gases in special furnaces. The reducing gases are mainly produced from natural gas or coal. The DRI are then melted in electric arc furnaces to produce steel. Different processes have been developed which mainly differentiate on the basis of the type of furnace adopted. Between all the commercial available processes, the Midrex represents the one with the largest market share, equal to the 60% in the 2020 [2]. For this reason, this process has been selected and investigated in this work.

1.2. Objective of the work

The aim of this work is to assess the techno-economic analysis of the integration of SEWGS in the MIDREX direct reduction process to decrease the carbon footprint of this steel production route. The analysis was carried out simulating different plants configurations, a conventional DR-EAF plant based on Midrex technology, a Midrex plant with a pre-combustion MDEA carbon capture section and a Midrex plant with a pre-combustion SEWGS carbon capture section.

2. Investigated plant configurations

2.1. Base DR-EAF plant

For this study the ArcelorMittal Montreal plant, located in Contrecœur (Quebec), Canada, was selected as base case since real plant data are available in literature [3], [4]. The data used in this work are reported in Table 1 and in Table 2.

Two main emissions points can be identified: the flue gas of the reformer and the electric arc furnace. About the flue gases, emissions are related to the utilization of the top gas with relevant amount of CO and CO_2 as fuel to supply the heat necessary to the reforming reaction. Furthermore, some additional natural gas is to be provided to the reformer. As mentioned above, the other emission point is related to the electric arc furnace where the DRI is melted and further prepared for steel production. In any case, the main contribution to the emissions of the whole process is given by the flue gas of the reformer.

The top gas, downstream the scrubber is divided into two streams; the one used as fuel for the reformer is roughly the 33% of the total, while the remaining part is recycled back and mixed with fresh natural gas in order to produce the reducing gases necessary for the reduction of the iron ores. The direct reduced iron then is sent to an electric arc furnace to be melted and produce steel.

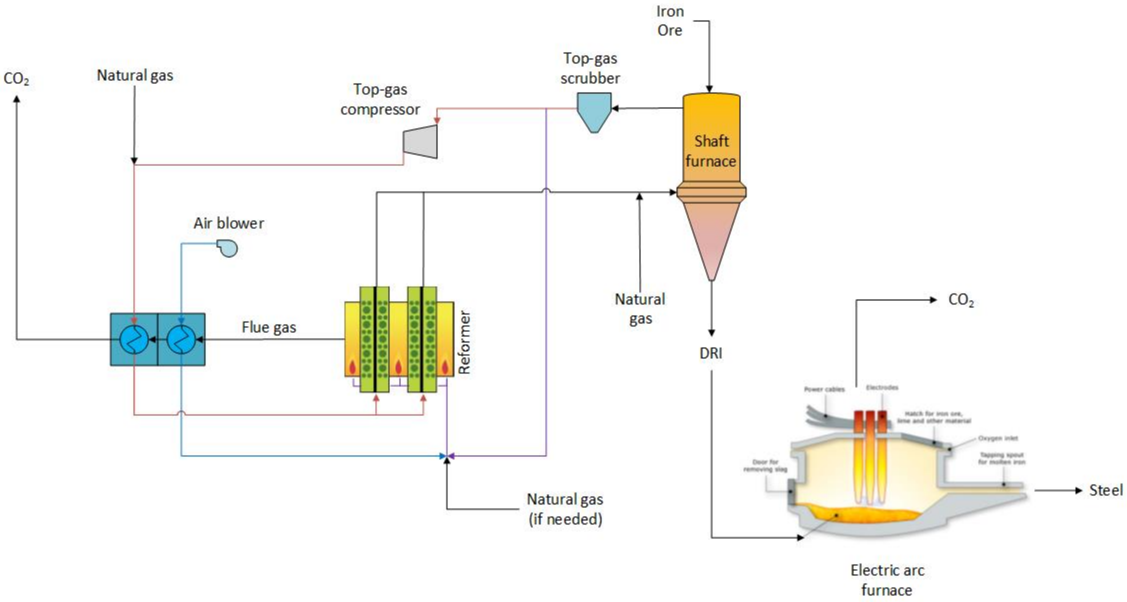

Fig 1: Conventional Midrex plant plus electric arc furnace

Table 1: Specifications of reducing gas, top gas and cooling gas

Stream	Temperature [°C]	Pressure [bar]	Mole flow rate [kmol/h]	Molar composition [%mol]					
				H_2	N_2	H_2O	CO	CO_2	CH_4
Reducing gas	957	n.a.	7841	49.66	1.76	4.28	32.71	2.40	9.08
Top gas	285	1.42	8611	40.28	1.02	19.03	19.58	17.09	2.95
Cooling gas	41	n.a.	1806	13.42	0.78	3.20	4.30	2.40	75.90

Table 2: Specification of iron ore and bottom product

Stream	Temperature [°C]	Pressure [bar]	Mass flow rate [kg/s]	Mass composition [%]					
				Fe_2O_3	Fe_3O_4	FeO	Fe	C	Gangue
Iron ore	-10	1.013	45.54	96.65	0.00	0.00	0.00	0.00	3.35
DRI	n.a.	n.a.	33.1	0.00	0.00	7.47	85.72	2.00	4.71

2.2. DR-EAF with pre-combustion MDEA carbon capture section

The top gas coming from the shaft furnace and then used as fuel for the reformer contains a high quantity of CO and CO_2. The direct reduction process can be decarbonized by shifting the CO to CO_2 in a WGS section and then capture the CO_2 in a MDEA carbon capture section. The whole conversion of CO into CO_2 is equal to 89% and it is achieved with three WGS reactors with an overall steam to CO ratio equal to 2.1. A split configuration is adopted with only 37% of the gas sent to the first WGS reactor. The products of the first reactor are then mixed with the remaining top gas and sent to the following WGS reactors to complete the conversion. Before to be shifted, the top gases are compressed to 8 bar in order to decrease the dimensions of the vessels and favor the CO_2 capture in the MDEA carbon capture section. The shifted gas is cooled to a temperature suitable to produce part of the steam necessary for solvent regeneration then it is further cooled to 40°C and the condensed water is removed. In the absorber column, the syngas is in contact with the lean solvent (MDEA) that absorbs the carbon dioxide. A decarbonized clean fuel exits at the top of the column while the CO_2 rich solvent exits from the bottom and it is sent to the stripping column to be regenerated. The high-purity CO_2 exits the stripper column at the top and the evaporated water is removed in a condenser. The CO_2-rich stream is then compressed up to 78 bar in a multistage compressor, liquefied being cooled to 25°C and pumped to 110 bar. The H_2 rich stream is then used as clean fuel in the reformer (Fig 2).

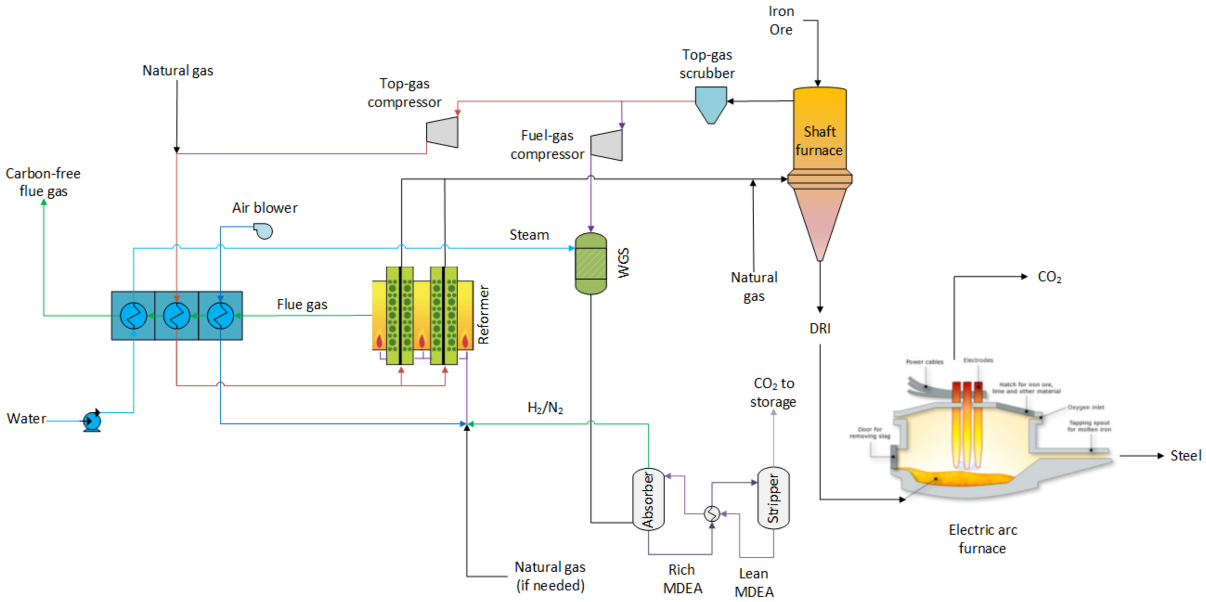

Fig 2: Midrex plant with pre-combustion carbon capture MDEA section plus electric arc furnace

2.3. DR-EAF with pre-combustion SEWGS carbon capture section

The plant layout of a DR-EAF plant with SEWGS carbon capture section is quite similar to the one described in section 2.2. The concept is the same, producing, from the top-gas, a H_2/N_2 mixture that can be used as fuel in the reformer. The main differences regard the pressure at which the WGS and the SEWGS reactors are operated but also the lower number of water gas shift reactors needed. SEWGS operating conditions, in terms of inlet pressure and temperature, purge and rinse consumption, are taken from literature [5] while recognizing that there is significant flexibility in the SEWGS system to be optimized specifically for integration in this scheme.

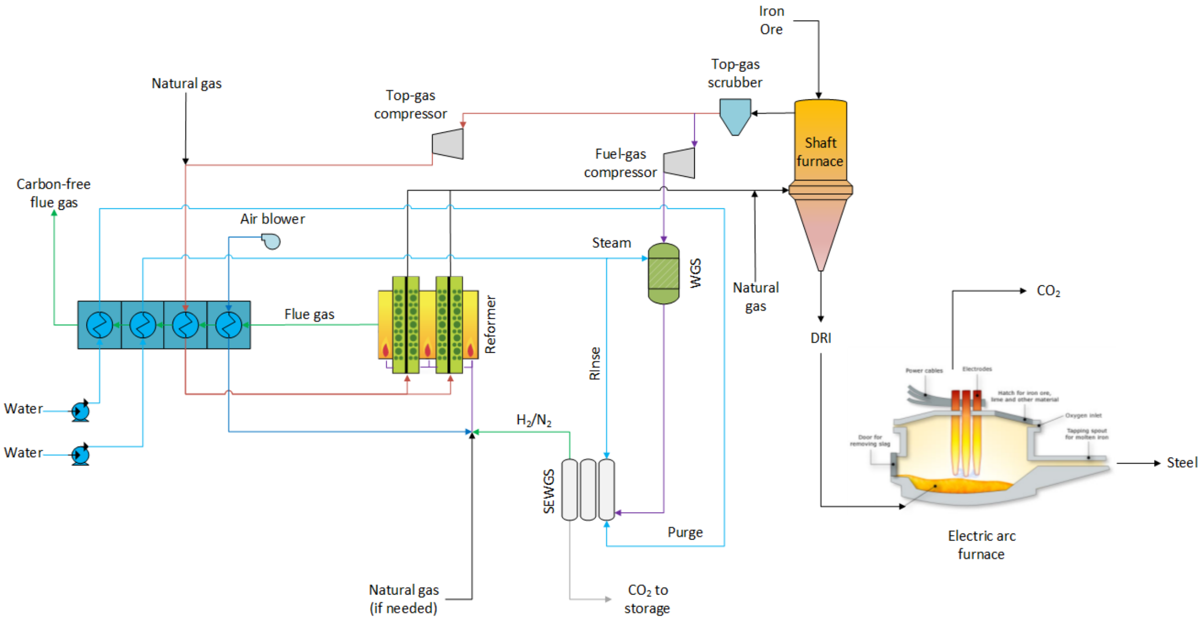

Fig 3: Midrex plant with pre-combustion carbon capture SEWGS section plus electric arc furnace

3. Methodology

3.1. Thermodynamic assessment

The plants described above have been simulated in Aspen Plus V11 except for the electric arc furnace which performances were taken from the literature [6], [7]. The model was calibrated to match the composition and the temperature of the reducing gas at the inlet of the shaft furnace available in literature. In addition, the shaft furnace has been modelled to reproduce the conditions of the top-gas as close as possible to the available plant data. The model of the reformer has been built by adopting a RGibbs reactor, to simulate the steam reforming reaction, and a RStoic reactor to simulate the burner. The shaft furnace has been simulated mainly with RGibbs and RStoic reactors in order to mimic the reactions occurring in it.

The power consumption of the electric arc furnace and the one of the rolling process considered in this work are taken from literature. The first one is equal to 400 kWh/t_{HRC} [6] while the latter is equal to 110 kWh/t_{HRC} [8]. The direct emissions of the electric arc furnace are considered equal to 0.1 t_{CO2}/t_{HRC} [7] while the ones related to the iron ore production are computed according to the carbon footprint associated with the electricity production and based on values found in [9]. The primary energy consumption of the pellets production, used to compute the PEC of the whole DRI/EAF process is equal to 2.58 GJ/t_{HRC} [6]. Furthermore, the primary energy consumption of the BF/BOF steel production route have been taken from literature [10] and considered constant in this work.

3.2. Economic assessment

The economic assessment was carried out comparing the solutions above described with the BF-BOF route and the DRI-EAF route. In the case of the BF/BOF route, the LCOHRC is the one computed with the methodology adopted in the INITIATE project and it is equal to 528.12 €/t_{HRC}. The cost of raw materials as well as the investment cost of the DRI-EAF route are taken from [1] and mean values are considered. The cost of the additional equipment was computed according to the bottom-up methodology described in [11]. The reference costs of the additional equipment are reported in Table 4. Additional assumptions made to carry out the economic assessment are shown in Table 3.

Table 3: Assumptions for the techno-economic analysis

	Unit	Value
Natural gas price	€/GJ (LHV)	20
Electricity price	€/MWh	150
CO_2 transport and storage	€/t_{CO2}	10
MDEA price	€/kg	1.25
Fixed O&M increase for CO_2 capture section	%	17.5
Electricity production efficiency	%	45
Natural gas boiler efficiency	%	92
Fixed charge factor	%	9.37
ton_{DRI}/ton_{HRC}	-	1.2

Table 4: Equipment reference cost

Component	Scaling factor	C_0 [M€]	S_0	f	Ref.
CO_2 capture unit (MDEA)	CO_2 mass flow rate, t/h	8.8	12.4	0.6	[12]
CO_2 compressor and condenser	Power, MW	9.95	13	0.67	[13]
Compressor	Power, MW	8.1	15.3	0.67	[12]
Boiler	Heat duty, MW	0.25	1	0.67	[12]
Pump	Volumetric flow, m^3/h	0.017	250	0.14	[12]
Heat exchanger	Heat transfer, MW	6.1	828	0.67	[12]
WGS	H_2 and CO flow rate, kmol/s	18.34	2.45	0.65	[12]
SEWGS single train	Inlet mole flow rate, kmol/s	8.88	1.56	0.67	[11]

3.3. Key Performance Indicators

The comparison between all the different cases investigated is made through economic and environmental Key Performance Indicators (KPIs) typical of this analysis and available in [5], [11] and [12]. The environmental indexes considered in this study are the Primary Energy Consumption (*PEC*), the specific CO_2 emissions (e_{CO2}), the CO_2 capture rate (*CCR*), the Specific Primary Energy Consumption for CO_2 Avoided (*SPECCA*) and CO_2 Avoidance (*CA*). The SPECCA indicator is defined as the additional primary energy required (in GJ) to avoid the emission of 1 ton of CO_2 producing the same amount of product. The economic performance is assessed in terms of Levelized Cost of Hot Rolled Coil (LCOHRC) and Cost of CO_2 Avoidance (CCA).

4. Results

The main results of the energy, environmental, and economic assessment are presented in this section.

4.1. Environmental results

The primary energy consumption, the CO_2 emissions and the relative KPIs are reported in Fig 4. The specific CO_2 emissions take into account the direct and indirect emissions of the DRI production, and the ones related to the electric arc furnace. The PEC of the BF/BOF route is considered independent of the carbon footprint of electricity production since it is supposed that all the electricity necessary to run the integrated steel mill is internally produced. On the other hand, the PEC of the DRI/EAF plants increases with the increase of the electricity carbon footprint. Indeed, the primary energy consumption associated to electricity generation is considered equal to zero for a renewable energy scenario (i.e. electricity carbon footprint equal to 0 kg_{CO2}/kWh) since no fossil fuels are consumed but it increases linearly with the electricity carbon footprint. The DRI/EAF+SEWGS plant import the same quantity of natural gas but a higher quantity of electricity with respect to the DRI/EAF base plant. For this reason, when renewable energy is considered, and so when the PEC of electricity generation is equal to zero, the PEC of the two plants is the same. As can be observed for certain values of the electricity carbon footprint, the PEC associated to the DRI/EAF plants is lower than the one of the BF/BOF route, reflecting in a negative SPECCA, meaning that less primary energy is consumed to produce the same amount of steel while reducing the CO_2 emissions.

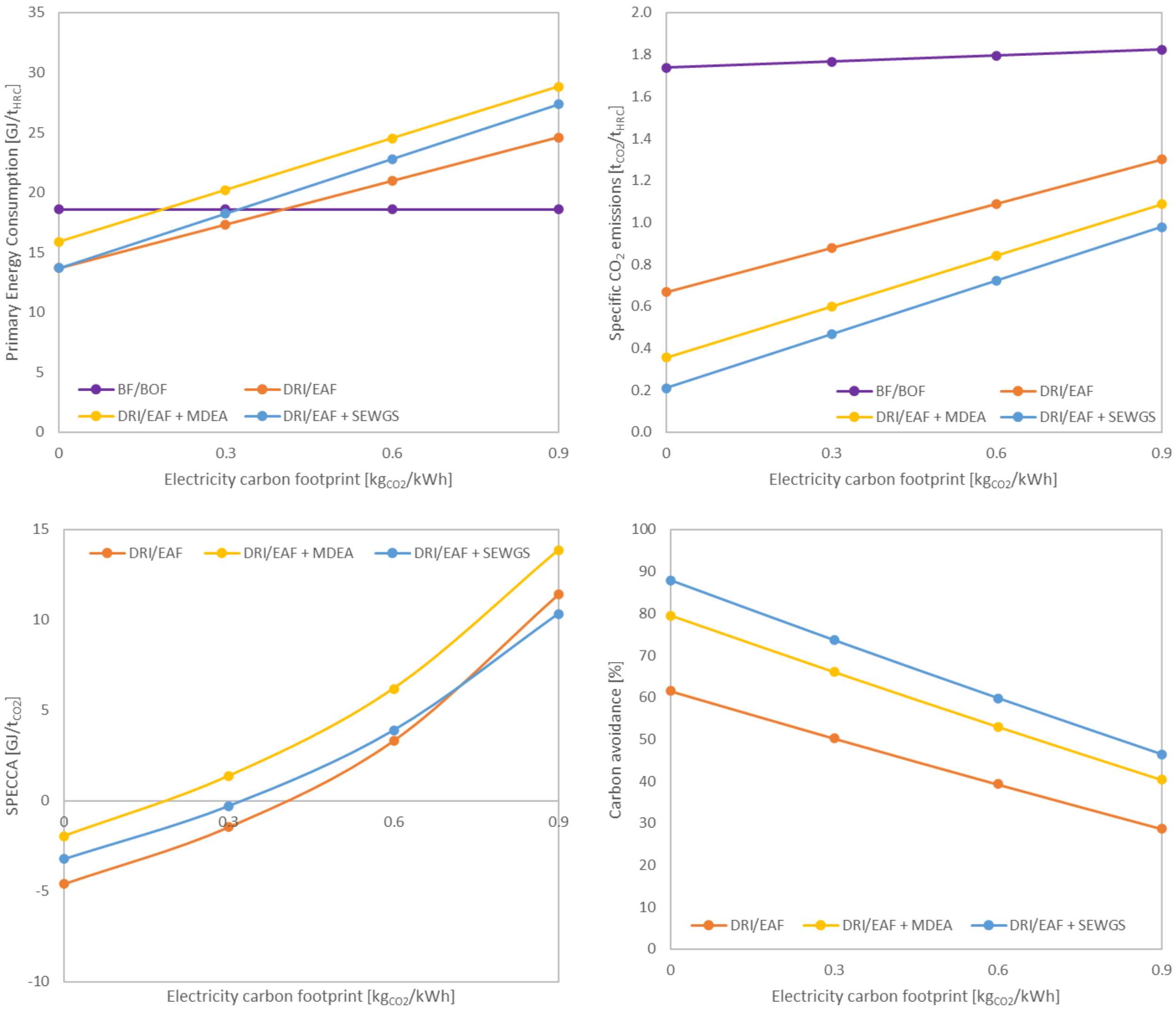

Fig 4: Specific CO_2 emissions, carbon avoidance, PEC and SPECCA of the investigated plant solutions with respect to BF/BOF route

The SEWGS integrated in the Midrex process allows the lowest specific carbon emissions with a SPECCA lower than the one of MDEA case. The main difference between the PEC of these two cases is given by the additional natural gas import necessary to regenerate the solvent in the Midrex+MDEA plant. When a renewable energy scenario is considered, the carbon avoidance of the case in which the SEWGS is integrated reach almost 90% respect to the BF/BOF route.

4.2. Economic results

The economic results, such as the levelized cost of hot rolled coil and the cost of CO_2 avoided are shown in Table 5 and in Fig 5. The levelized cost of hot rolled coil in the case of all DRI/EAF investigated plants is higher than the reference BF/BOF one. As can be observed what penalizes the most the MDEA solution is the higher import of natural gas with respect to the base case and the case with the implementation of SEWGS. The cost of CO_2 avoided in the case of the DRI/EAF+SEWGS plant is slightly higher than the one of the base case even if the SEWGS-case allows a deeper decarbonization of the steelmaking process.

Table 5: LCOHRC for the plants investigated

	BF/BOF	DRI/EAF	MDEA	SEWGS
LCOHRC, €/t_{HRC}	538.12	591.65	674.87	628.42

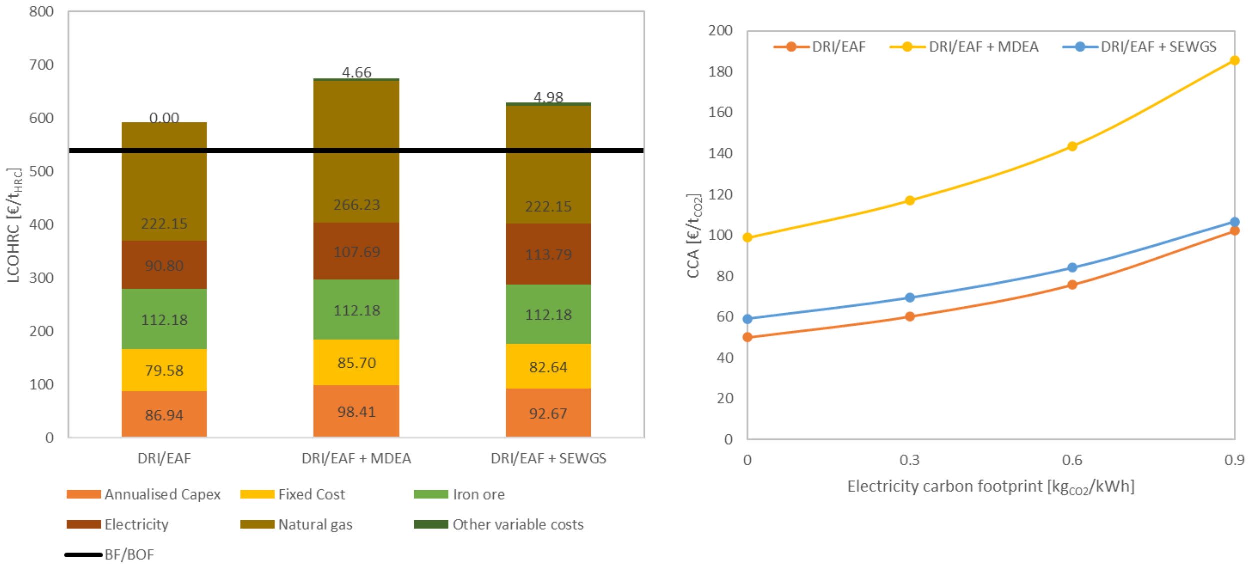

Fig 5: LCOHRC and Cost of CO_2 avoided with respect to BF/BOF route

5. Conclusion

This work discusses the techno-economic assessment of the integration of the SEWGS technology in a Midrex/EAF plant for GHG mitigation in the steelmaking sector. The analysis is carried out by comparing different plants through economic and environmental KPIs with respect to BF/BOF route. Real plant data, available in literature have been used to model a Midrex/EAF plant. The same data have been used to investigate the possibility of reducing the carbon footprint of the DRI/EAF route by adopting a MDEA pre-combustion carbon capture section or the SEWGS technology. The analysis shows promising results about the integration of the SEWGS in the DRI/EAF process since a reduction of the CO_2 emissions close to 90%, with respect to the BF/BOF route, can be reached in a renewable energy scenario. In addition, the CCA varies between 60 €/t_{CO2} to 100 €/t_{CO2} and it is quite similar to the CCA of the DRI/EAF plant.

Furthermore, considering that the DRI/EAF route is already globally adopted on industrial scale, the commercial integration of the SEWGS technology could be probably viable in the next future.

For sake of consistency, it must be underlined that the performances of SEWGS were taken from literature and so the analysis can be upgraded considering the performances of the SEWGS optimized for this process.

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