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Techno-economic assessment of the FReSMe technology for CO_2 emissions mitigation and methanol production from steel plants

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A B S T R A C T

The iron and steel industry accounts for 6 % of the global CO_2 emissions and it is one of the main hard-to-abate sectors that must be un-locked to reach climate neutrality in the coming decades. The objective of this work is to assess the economics of the FReSMe (From Residual Steel gases to Methanol) process for reducing the carbon footprint of conventional steel plants based on the Blast Furnace route. This reduction is achieved by capturing and converting part of the steel plants residual gases into methanol. The process includes the Sorption Enhanced Water Gas Shift (SEWGS) technology to treat the residual gases separating the CO_2 and producing a H_2-rich stream. The latter can be recirculated back to the steel plant to cover part of its primary energy demand or reacted together with part of the separated CO_2 to synthetize methanol. The CO_2 excess can be used for underground storage. Four different process configurations with different methanol production capacities are investigated. Costs and performances of each configuration are assessed and compared to two reference cases. Results show that the FReSMe process allows to avoid around the 60 % of the overall steel plant CO_2 emissions, while the reference plant with post-combustion capture in the power section only 18 %. The cost of CO_2 avoided is in the range 40.6 €/t_{CO2} – 46.2 €/t_{CO2}. When no carbon tax is considered, the optimal methanol production capacity results 600 t/day with a Levelized Cost of Hot Rolled Coil of around 520 €/t_{HRC}, 9.4 % higher than in the base case (476 €/t_{HRC}). With a carbon tax rate above 40.6 €/t_{CO2}, the optimal configuration has a methanol production capacity of 300 t/day and it ensures higher emissions reduction and lower costs than conventional post-combustion carbon capture systems.

1. Introduction

It is commonly stated that climate change is one of the most serious environmental issues and greenhouse gases (GHG) emissions should be reduced in every field of activity. 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, iron and steel industry, which accounts for 6 % of global CO_2 emissions and 16 % of total industrial emissions of CO_2 worldwide, has a large potential to reduce emissions [1]. The residual gases arising from steel production processes in a steel plant are used as fuel in different process units within the plant. In case of integrated steel plants, the excess is supplied to a power plant to produce power, process steam, and/or heat, which are used within the plant and sometimes also for external users in the community [2]. Typically, around 50 % of the overall CO_2 emissions derive from the power/heat generation section; the remaining CO_2 emissions are distributed across several locations in the steel plant (i.e. coke oven batteries, sinter plant, hot stoves) [3–5]. Different strategies can be adopted to mitigate carbon dioxide emissions of conventional steel plants based on the Blast Furnace (BF) route. One way is increasing the energy efficiency of the steel production process: this has been effectively fostered during last years, indeed, the steel production energy intensity has decreased from 25 GJ per ton of crude steel in 2005 to 20 GJ per ton in 2012 [6]. However, the resulting amount of CO_2 emissions is still far from the target set for the iron and steel industry [3]. Another possible way to reduce the emissions from the steel sector is to use hydrogen as an auxiliary reducing agent for the blast furnace to partly replace the CO derived from burning pulverized coal or coke. Yilmaz et al. [7] investigated this option through a detailed process model and they showed that the CO_2 emissions of the blast furnace can be reduced by 21.4 % with respect to its typical operation with pulverized coal

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Nomenclature

Acronyms

BF	Blast Furnace
BFG	Blast Furnace Gases
BOFG	Basic Oxygen Furnace Gases
CCA	Cost of CO_2 avoided [€/t_{CO2}]
CCS	Carbon Capture and Storage
COG	Coke Oven Gases
FReSMe	From Residual Steel Gases to Methanol
GHG	Greenhouse Gases
GT	Gas Turbine
HRC	Hot Rolled Coil
HRSC	Heat Recovery Steam Cycle
HRSG	Heat Recovery Steam Generator
LCOHRC	Levelized Cost of Hot Rolled Coil [€/t_{HRC}]
LCOM	Levelized Cost of Methanol [€/t_{MeOH}]
LHV	Low Heating Value [MJ/kg]
MDEA	Methyldiethanolamine
MEA	Monoethanolamide
NG	Natural Gas
NGGT	Natural Gas fired Gas Turbine
OBF	Oxygen Blast Furnace
RG	Residual gases
PEC	Primary Energy Consumption
SEWGS	Sorption Enhanced Water Gas Shift
ST	Steam Turbine
SPECMeOH	Specific Primary Energy Consumption for Methanol Production [MJ/kg_{MeOH}]
TEC	Total Equipment Cost [€]
TPC	Total Plant Cost [€]
WGS	Water Gas Shift

Symbols

C	Cost
d	Discount rate
E	CO_2 emissions
j	Inflation rate
m	Mass
$\dot{m}$	Mass flow rate
P	Electric Power
$\widetilde{p}$	Price
S	Size

Subscripts

C,RG	residual gases compressor
C,CO2	CO_2 compressors
el	electric
memb	membrane system
MeOH	methanol
net	net

injection. To achieve higher emissions reductions, processes for carbon capture and storage (CCS) should be effectively adopted in steel plants based on the BF route [3].

1.1. Carbon capture & storage (CCS) systems for steel plants

CCS technologies in steel plants can be distinguished into two main categories: post-combustion systems and pre-combustion systems. Post-combustion capture technologies represent the most conventional solution that can be applied both to the power generation off-gases and to the other main emission points in the steel plant. However, the latter option is more challenging and expensive since it would require several small capture sections, one for each emission point [1]. Therefore, post-combustion based CCS is typically applied to the sole power section which limits the CO_2 abatement to around 50 % of the overall steel mill emissions. On the other hand, pre-combustion systems can be directly applied to the steelworks arising gases which can be treated to remove their carbon content and then used as clean fuel in the steel plant and in the power generation section. As a consequence, the pre-combustion option has the highest CO_2 reduction potential, since all the carbon of the steelworks arising gases can be theoretically recovered [1].

Arasto et al. and Tsupari et al. investigated the post-combustion carbon capture technology applied to integrated steel plant [8,9]. They compared conventional monoetanolamine (MEA) based solvent scrubbing process with two alternative solvents showing that the MEA system has the lowest energy intensity. In a second paper, Arasto et al. [10] compared the post-combustion capture technology to an oxygen blast furnace (OBF) layout. 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) are sent back to the blast furnace, lowering the coke demand [11]. Arasto et al. [10] showed how the cost of CO_2 avoided is equal to 35 €/t_{CO2} for OBF with respect to 50 €/t_{CO2} for post-combustion. On the other hand, the post-combustion capture technology is considered commercially available in the near future [10].

When it comes to pre-combustion systems, a promising solution is the adoption of the Sorption Enhanced Water Gas Shift (SEWGS): SEWGS reactor simultaneously converts CO into H_2 via Water Gas Shift reaction and separates the CO_2 producing two streams: a H2-rich stream and a CO_2-rich stream. Compared to conventional wet scrubbing technologies, the SEWGS system reduces thermal cycling and requires a smaller pre-Water Gas Shift (WGS) unit [12–14]. The application of the SEWGS technology for integrated steel plant has been investigated in previous works [1,3]. In [3], SEWGS performance are compared to both post-combustion and pre-combustion absorption processes using amine technologies. Results showed that the adoption of the SEWGS technology allows to achieve higher CO_2 avoidance than conventional post-combustion MEA process with lower specific primary energy consumptions. In [1] a techno-economic assessment of the SEWGS technology applied to integrated steel plants is presented. Results showed that the adoption of the SEWGS allows to achieve higher CO_2 avoidance than conventional post-combustion with a cost of CO_2 avoidance around 33 €/t_{CO2}. However, the SEWGS was adopted to treat only the residual gases headed for the power generation, hence the CO_2 emissions reduction was limited to around 38 % of the overall steel plant emissions.

1.2. Methanol production from steel plant residual gases: a CCU approach

As an alternative to CCS technologies, it is of great interest the use of steel plants excess gases for the production of higher value products, such as fuels or chemicals instead of heat and power: this approach is at the basis of the Carbon Capture and Utilization (CCU) technologies. Commercial technology to produce methanol from steel production residual gases already exists and is of particular progress in China. In 2009, China had a production capacity of approximately 27 Mt of methanol per year, of which the 15 % was obtained from steel plants coke oven gases (COG) [15]. Ghanbari et al. [16] have investigated an integrated steel plant producing methanol as valuable by-product in addition to heat and electricity. The objective was to minimize the cost of steel production considering different options for operating the blast furnace

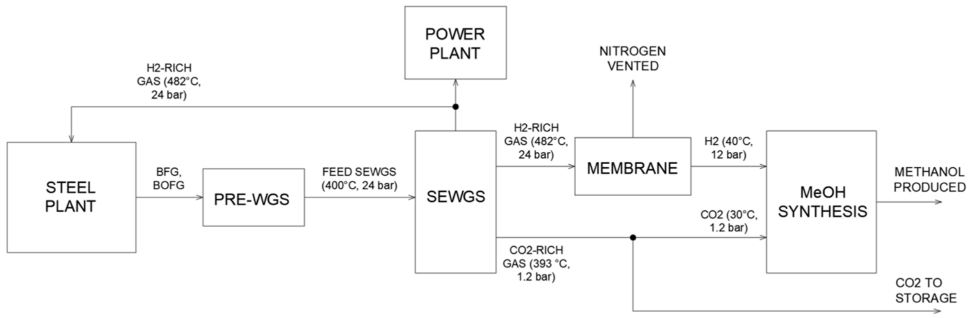

Fig. 1. Block flow diagram of the FReSMe process.

Table 1
Main performances of the considered steel plant.

	Unit	Value
Operating hours	hours	8760
HRC production	Mt_{HRC}/y	4
Electric power consumption	kWh/t_{HRC}	400.1
Specific CO_2 emissions (base case, excluding the power plant)	kg_{CO2}/t_{HRC}	1112

and different auxiliary fuels (oil, natural gas and pyrolyzed biomass). Lundgren et al. [5] analysed from a techno-economic point of view different processes for methanol production from steel mills residual gases and biomass based synthesis gas, showing that if only the residual gases are utilized in the process, methanol can be produced with costs around 510 €/t_{MeOH}. Recently, Girod et al. [17] presented the results of an experimental campaign carried out at the Thyssenkrupp Steel Europe site in Duisburg, Germany to demonstrate the methanol synthesis from real steel mill gases. The experimental setup included a CO shift unit with a high-temperature and a low-temperature shift reactor, followed by a methanization unit, and a CO_2 separation unit. However, the analysis of the obtained data was challenging due to the significant thermal deactivation of the shift reactors catalysts occurred especially during the first weeks.

1.3. FReSMe process

The FReSMe (From Residual Steel Gases to Methanol) process is designed to reduce CO_2 emissions of a steel plant and simultaneously produce methanol, exploiting the SEWGS technology to treat the steel-making residual gases [18]. The process has been developed in the frame of the European H2020 FReSMe project, which is the follow up of two previous EU funded research projects: STEPWISE, that focused on the application of the SEWGS technology for the CO_2 emissions mitigation of integrated steel plants [19], and MefCO_2 that investigated the methanol production from carbon dioxide [20]. The FReSMe process was described in previous work [21] and it is schematically represented in Fig. 1. The residual gases produced in the steel plant are divided into three main streams: basic oxygen furnace gases (BOFG), blast furnace gases (BFG), and coke oven gases (COG). The COG is recirculated to the steel plant, while all of the available BFG and BOFG are compressed to around 24 bar sent to a pre-WGS unit and then to the SEWGS rector. In the latter a hydrotalcite-based sorbent is operated using a pressure swing adsorption approach between 24 and 1.2 bar. 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 nearly reached, the material is regenerated by pressure reduction (around 1.2 bar) and purging with superheated steam (at around 400 °C), producing a hot low pressure CO_2-rich product. Prior to the pressure release, rinse steam is added to enhance the CO_2 product purity.

The H_2-rich gas at the outlet of the SEWGS is divided into three streams: one is sent to the steel plant where it is used as clean fuel, one is sent to a power plant to produce electric energy, and the other is purified in a membrane system and then used to synthetize methanol. The CO_2-rich gas is used for methanol production while the excess is sent for storage. The membrane system includes two stage of membranes and corresponding compression to combine high H_2 recovery and high H_2 purity; the separated gas, mainly nitrogen, is released in the environment. The methanol unit is composed by the methanol production reactor and a purification section; the latter is made by two distillation columns which require low pressure steam. Overall, four streams of super-heated steam at different pressures and temperatures are required for pre-WGS, purge and rinse for the SEWGS, and methanol distillation. Such steam can be partially obtained through heat recovery cooling down the hot flows available in the process.

As part of the hydrogen separated in the SEWGS is circulated back to the steel plant reducing the primary fuel input, the FReSMe technology has the potential to reduce the CO_2 emissions by more than 50 %. This aspect, as well as the production of a valuable product such as methanol, represent two important characteristics which make the FReSMe process a potentially promising solution for the steel production decarbonization.

1.4. Objective of the work

This work aims at assessing performance and cost of the FReSMe technology. Different configurations of the FReSMe process, characterized by different amounts of methanol produced and hence by different CCU/CCS balances, are investigated. Energy performances and costs of the analysed cases are compared to a base case (steel plant without CO_2 capture) and a reference case (steel plant with post-combustion CO_2 capture using amine scrubbing). Therefore, the optimal CCU/CCS balance will be assessed and the potential of the FReSMe technology for the emissions mitigation and the methanol production from steel plants residual gases will be determined. The paper is divided as follows: Section 2 presents the methodology adopted for the techno-economic assessment, Section 3 describes the base and reference cases as well as the different investigated configurations for the FReSMe system, Section 4 reports the obtained results and Section 5 draws the main conclusions of the work and anticipates possible future developments.

2. Methodology

2.1. Thermodynamic assessment

The thermodynamic analysis of the different plant configurations is performed according to the methodology and the assumptions reported in this subsection.

The steel plant is treated as a black box whose performances are taken from a previous work [1]. It provides updated techno-economic performances of a reference steel mill whose characteristics are based on the 2013 Report of the International Energy Agency Greenhouse Gas

Table 2
Main design parameters for SEWGS.

	Unit	Value
Number of trains	–	8
Number of columns per train	–	8
Total number of columns	–	64
Column diameter	m	4.5
Column length	m	12
Feed temperature	°C	400
Feed pressure	bar	24
CO_2 Product pressure	bar	1.2
S/C rinse	mol steam/mol carbon	0.3
S/C purge	mol steam/mol carbon	0.6

Table 3
Main assumptions for power plant, CO_2 compression, and boiler and NG specifications.

	Unit	Value
Residual gases compressors polytropic efficiency	%	88
Residual gases compressors mechanical efficiency	%	98
Boiler efficiency	%	95
CO_2 compressors specific consumption	kJ/kg_{CO2}	312
Natural Gas molar composition:	%mol	
CH_4		83.9
C_2H_6		9.20
C_3H_8		3.30
C_4H_{10}		1.20
C_5H_{12}		0.20
CO_2		1.8
N_2		0.4
Natural Gas Low Heating Value	MJ/kg	46.2

Table 4
Main assumptions for the economic assessment.

	Unit	Value
Plant lifetime (N_{years})	years	25
FReSMe plant availability	%	92.5
Discount Rate (d)	%	10
MeOH selling price ($\widetilde{p}_{MeOH}$)	€/t	410
HRC selling price ($\widetilde{p}_{HRC}$)	€/t	507
Electricity purchasing price	€/MWh	30
Electricity selling price	€/MWh	15
NG purchasing price	€/GJ	5.2
Specific CO_2 emissions for external electricity production	kg_{CO2}/MWh	460
Installation costs	% of TEC	66
Indirect costs	% of (TEC + Installation)	14
Contingency and owner's costs	% of (TEC + Installation + Indirect)	15
Construction time	years	3

R&D Programme (IEAGHG) [2]. The steel plant is unchanged between the base, reference and FReSMe cases. The main assumptions related to the steel plant are reported in Table 1 together with the specific CO_2 emissions of the steel mill excluding the power plant, which have to be accounted on top of the emissions related to the residual gases treated in the process.

The pre-WGS unit is modelled in Aspen Plus using the Peng-Robinson Equation of State and assuming an adiabatic reactor fed at 340 °C and 24 bar and operating with a steam-to-CO ratio (S/CO) of 1.5 [22]. For SEWGS performance, a dedicated model developed by TNO has been adopted. In particular, 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, and (iii) a column module, describing the packed bed behaviour and allowing effective accounting of the performance of the different columns in the cycle [1,12–14]. Different settings may be considered for the SEWGS, however this work focuses on the integration of this technology with the power and methanol production sections rather than on the optimization of the SEWGS operating conditions. Therefore, for all of the cases the design parameters reported in Table 2 are considered.

The membrane system is assumed to be composed by a double polymeric membrane with two compression stages: one between the two membranes and one downstream the second one. A recycle loop ensures both high H_2 yield and high H_2 purity. The system is modelled in Aspen Plus assuming a polytropic efficiency of 85 % for both the compressors and the membrane performances obtained through experimental results carried out at the FReSMe pilot plant in Luleå (Sweden). The membrane system electric power consumption specific to the separated hydrogen mass is equal to 2.8 kWh/kg_{H2}.

The methanol production capacity is varied for the different plant configurations considering identical modules for the methanol synthesis and purification and varying the number of modules from one to four. The performance of each module is taken from the data of the FReSMe European Project [18] and provided by the project partner Carbon Recycling International (CRI) [23]. The module capacity is 300 t/day, with an electric power consumption of 5 MW and a hydrogen conversion rate of 98 %. For each number of modules, three different plant configurations have been investigated. They are characterized by different heat exchangers networks to recover the heat available in the hot gases and produce the steam required by the process: i) the first configuration has a limited number of heat exchangers and exploits the steam turbine within the power plant to bleed the steam required by the process and to expand the steam produced through process heat recovery; furthermore, a Natural Gas fired Gas Turbine (NGGT) is adopted to produce additional electric energy and the hot gases at the turbine outlet are cooled down producing the steam required for the pre-WGS; ii) the second configuration aims to minimize the bleedings from the steam turbine by adopting additional heat exchangers to recover the heat available in the hot streams; also in this case a NGGT is included to produce electric power and steam for the pre-WGS; iii) the last configuration is similar to the second but involves a steam boiler fed with the H_2-rich gas at the outlet of the SEWGS. For the sake of brevity, only the third configuration is described and analysed in this paper, as it resulted the best ones from both the economic and environmental point of views.

For each number of methanol modules, the number and size of the heat exchangers are estimated through the software Aspen PLUS. The electric power consumption of the residual gases compressor ($P_{C,\,RG}$) has been evaluated using Aspen PLUS assuming the compressors efficiencies reported in Table 3.

The electricity consumption associated with the CO_2 compression ($P_{C,CO2}$) is estimated considering the specific compression work obtained in the previous work [1] and reported in Table 3. The net electric power produced for each investigated plant configuration is calculated through Eq. 1, where P_{GT}, P_{ST}, and P_{NGGT} are the power produced by H_2-rich fired gas turbine (GT), steam turbine (ST), and NGGT, respectively, and P_{memb} and P_{MeOH} are the electricity demand of the membrane system and the methanol production units. The power consumption of the pumps is not considered since it is negligible with respect to the other electric consumptions.

$$P_{net} = P_{GT} + P_{ST} + P_{NGGT} - P_{C,\,RG} - P_{C,CO2} - P_{memb} - P_{MeOH} \quad (1)$$

2.2. Economic assessment

The economic analysis is performed computing first of all the Capital Expenditure (CAPEX), the Operating Expenditure (OPEX) and the revenues for each investigated case. The main assumptions adopted are taken from the FReSMe European project data and are listed in Table 4.

The MeOH selling price is assumed equal to the March 2021 market

Table 5
CAPEX related to steel plant, pre-WGS, SEWGS, membrane system and MeOH synthesis unit.

Component	Capital Cost (M€)	Reference
Steel plant	4590.2	[1]
pre-WGS	2.2	FReSMe Project data [18]
SEWGS	271	Adapted from [1]
Membrane system (for 1 MeOH unit)	148.5	Adapted from [28]
N. 1 MeOH synthesis unit	43.9	FReSMe Project data [18]

Table 6
Reference costs and sizes and scaling factors for equipment cost assessment.

Component	Reference cost *Co* (M€)	Reference size *So*(MW)	Scaling factor *f* (-)
Gas turbine	49.4	272.1	0.45
HRSC	60.2	95.1	0.67
CO_2 compressors and condenser	44	50.5	0.67
Residual gases compressors	8.1	15.3	0.67

Table 7
Main assumptions for FReSMe OPEX assessment.

	Unit	Value
Steel plant OPEX	M€/year	1372.7
Number of staff for FReSMe plant	–	30
Staff hourly rate	€/h	40
Maintenance cost	% of FreSMe CAPEX	2.5
Insurance cost	% of FreSMe CAPEX	1.5
Process water cost	€/t	6
Cooling water cost	€/t	0.35
Pre-WGS and SEWGS lifetime	years	5

price of Methanol according to Methanex [24]; analogously, the HRC selling price is assumed equal to the average HRC price in Northern Europe for April 2020 [25]. In order to assess the impact of the assumed selling prices on the FReSMe plants profitability, two tailored sensitivity analyses are carried out and their results are reported in Subsection 4.3. The value of specific CO_2 emissions for external electricity production is taken from the Covenant of Mayors 2017 Technical Annex [26]. Lastly, the electricity purchasing price is assumed according to the International Energy Agency (IEA) 2020 Report [27]. The CAPEX related to steel plant, pre-WGS unit, SEWGS unit, membrane system, and methanol synthesis unit are summarized in Table 5; the reported values already account for installation, indirect, contingency, and owner's costs.

All the other costs of the investigated plants are calculated through the same approach adopted in the previous work [1]: firstly the Total Equipment Cost (TEC) is calculated and then the CAPEX is obtained summing installation, indirect and contingency costs. For gas turbines, heat recovery steam cycles (HRSCs), and residual gases and CO_2 compressors Eq. 2 is applied to evaluate the equipment cost as function of the component size (S), the cost (Co) of a reference component with size So, and a scaling factor (f); all the reference values are taken from the previous work [1] and are reported in Table 6. For heat exchangers, pumps, and separators the Aspen Economic Analyzer is adopted to estimate the equipment cost.

$$C = Co\left(\frac{S}{So}\right)^{f} \quad (2)$$

Once the TEC is known, the Total Plant Cost (TPC) is calculated accounting for the installation, indirect, contingency, and owner's cost according to the percentage values reported in Table 4. Finally, the overall CAPEX is computed summing the calculated TPC to the costs reported in Table 5.

The overall OPEX is calculated considering the steel mill OPEX obtained in previous work [1] and summing the operating costs related to the FReSMe plant. The latter are assessed accounting for NG and electricity purchase, labour, maintenance, and insurance costs, process and cooling water consumption, and pre-WGS and SEWGS replacement. Such costs are evaluated according to the assumptions reported in Table 7.

The annual revenues are assessed accounting for an annual revenue of 47.1 M€ due to the Steel Plant by-products (coke by-products, slag, and argon) sale [1], and the electricity sale in case of overproduction. Moreover, in order to compute the Levelized Cost of Hot Rolled Coil (LCOHRC) and Levelized Cost of Methanol (LCOM), the revenues coming from the methanol and HRC sales are considered, respectively (see Section 2.3). Interests due to debts with credit institutions and taxes are not considered.

2.3. Key performance indicators

The comparison between the different layouts is made on the basis of economic and environmental Key Performance Indicators (KPIs). In detail three economic indexes are considered: CAPEX, Levelized Cost of Hot Rolled Coil (LCOHRC), and Levelized Cost of Methanol (LCOM). The LCOHRC is calculated through Eq. 3 accounting for CAPEX, OPEX, revenues (REV) due to electricity and by-products sale, and revenues coming from the methanol sale. In the equation, $\tilde{p}_{\mathrm{MeOH}}$ is the methanol selling price and d is the discount rate reported in Table 4. Analogously, the LCOM is evaluated through Eq. 4 taking into account the revenues deriving from the HRC sold at a price $\tilde{p}_{HRC}$. Taxes on the carbon dioxide emissions have an important impact on the steel production process economics hence they should be taken into account for the assessment of the LCOHRC and LCOM. However, the carbon tax rate changes significantly among the different countries which have implemented it. For instance, in April 2021 the highest carbon tax in Europe is implemented in Sweden and is 116 €/t_{CO2}, followed by Switzerland, 86 €/$t_{CO2,}$ and Finland, 62 €/$t_{CO2,}$ then France has a carbon tax of 45 €/t_{CO2}, and UK and Spain levy a tax of 21 €/t_{CO2} and 15 €/t_{CO2}, respectively [29]. Therefore, if a carbon tax is included in the calculations, the results would be extremely affected by the country where the analysis is conducted. Hence, in order not to limit the generality of the results, no taxes on the carbon dioxide emissions are considered to calculate the LCOHRC and LCOM. On the other hand, the effect of the carbon tax on the system economics is evaluated by means of a tailored sensitivity analysis in Subsection 4.3.1.

$$LCOHRC = \frac{CAPEX + \sum_{i=1}^{N_{years}} \frac{OPEX(i) - REV(i) - \tilde{p}_{MeOH}\cdot \dot{m}_{MeOH}}{(1+d)^{i}}}{\sum_{i=1}^{Nyears} \frac{\dot{m}_{HRC}}{(1+d)^{i}}} \quad (3)$$

$$LCOM = \frac{CAPEX + \sum_{i=1}^{N_{years}} \frac{OPEX(i) - REV(i) - \tilde{p}_{HRC}\cdot \dot{m}_{HRC}}{(1+d)^{i}}}{\sum_{i=1}^{Nyears} \frac{\dot{m}_{MeOH}}{(1+d)^{i}}} \quad (4)$$

Regarding the environmental indexes, the first KPI related to CO_2 capture systems is the CO_2 avoidance, defined by Eq. 5 where E_{base} are the specific CO_2 emissions of the base case described in Subsection 3.1 and E_{FReSMe} are the specific emissions related to each investigated configuration of the FReSMe plant.

Table 8
Residual gases specifications.

	Units	BOFG	BFG	COG
Temperature	°C	25	25	25
Pressure	bar	1	1	1
Mole Fractions				
CO_2	%mol	19	23	2
CO		58	24	5
H_2		3	4	62
N_2		20	49	7
CH_4		0	0	24
Mass Flows	kg/s	13.3	276.2	9.3
LHV	MJ/kg	5.7	2.5	38.2
Power	MW	75.3	698.8	355.3

Table 9
Specifications of H_2-rich and CO_2-rich gases, H_2 to methanol synthesis, and CO_2-dry to methanol synthesis. The flow rates indicated with an asterisk are referred to one single MeOH module.

	Unit	H_2-Rich	CO_2-rich	H_2 to MeOH	CO_2-dry to MeOH
Pressure	bar	24	1.2	40	40
Temperature	°C	482	393	12	1.2
Molar flow rate	kmol/s	7.28	10.00	0.33*	0.12*
Mass flow rate	kg/s	137.32	293.12	0.81*	5.10*
Mole Fractions	%mol				
H_2O		3.4	54.7	–	3.0
H_2		34.4	0.6	99.0	1.3
CO		2.4	0.1	–	0.2
CO_2		0.8	43.3	1.0	92.9
N_2		59.2	1.2	–	2.6

$$CO_2\ avoidance\ [\%] = \frac{E_{base}\left[\frac{kg_{CO2}}{t_{HRC}}\right] - E_{FReSMe}\left[\frac{kg_{CO2}}{t_{HRC}}\right]}{E_{base}\left[\frac{kg_{CO2}}{t_{HRC}}\right]} \tag{5}$$

The second KPI related to carbon capture systems is the Cost of CO_2 Avoided (CCA), defined as:

$$CCA\left[\frac{€}{t_{CO2}}\right] = \frac{LCOHRC_{FReSMe}\left[\frac{€}{t_{HRC}}\right] - LCOHRC_{base}\left[\frac{€}{t_{HRC}}\right]}{E_{base}\left[\frac{t_{CO2}}{t_{HRC}}\right] - E_{FReSMe}\left[\frac{t_{CO2}}{t_{HRC}}\right]} \tag{6}$$

Lastly, another KPI is introduced to assess the energy intensity of the methanol production through the FReSMe process: the Specific Primary Energy Consumption for Methanol Production (SPECMeOH). The latter is evaluated comparing the Primary Energy Consumption (PEC) of the FReSMe process with the base case one. Since the PEC of the steel plant is equal for all of the investigated cases, the SPECMeOH will depend only on the electricity import and the NG demand of the FReSMe process. A factor (f_{el}) of 0.4 has been assumed to assess the PEC for external electricity production. The SPECMeOH will be then compared to typical values obtained for conventional methanol synthesis from NG.

3. Investigated plant configurations

For all of the investigated plant configurations, the residual gases mass flow rates and specifications reported in Table 8 are considered. Only the BOFG and the BFG are used in the process, while COG is retained to the steel plant.

For all the cases it is assumed that, in addition to the 355.3 MW of LHV-based power provided by the COG, 301 MW are required by the steel mill to cover part of its primary energy demand: for the base and reference cases such thermal power is delivered retaining part of the BFG to the steel plant, while for the FReSMe cases it is covered with the H_2-rich gas produced by the SEWGS.

3.1. Base and reference cases

The base and reference cases are described in the previous work [1] and consider direct electricity generation with the steel plant residual gases with and without carbon capture. For both cases, 118.9 kg/s of BFG are sent back to the steel plant to be used as fuel (301 MW), hence only 157.3 kg/s of BFG are available for the power production, along with the BOFG. The mixture of the two gases is burned in a combined cycle composed by two identical E-class gas turbines coupled with a three-pressure level and reheat type HRSC. For the sole reference case a post-combustion capture section with conventional MEA is included to treat the exhaust gases of one of the two HRSGs. The power plant operates with a net electric efficiency of 49.4 % and 36.8 % for the base and reference cases, respectively [1]. Moreover, the carbon capture system allows a reduction of the power plant CO_2 emissions from 1835 kg_{CO2}/MWh in the base case to 1337 kg_{CO2}/MWh in the reference case. The capital and operating costs for the steel plant and the power sections of these two cases are taken from the same work [1].

3.2. FReSMe cases

When the FreSMe process is considered, the 301 MW required by the steel plant are covered with the H_2-rich produced in the SEWGS, hence all of the available BFG and BOFG are used to feed the process. This leads to a decrease of the steel plant specific CO_2 emissions from the value reported in Table 1, 1112 kg_{CO2}/t_{HRC}, to 479.4 kg_{CO2}/t_{HRC}. The pre-WGS and SEWGS pressure is set to 24 bar and the residual gases compressor requires an electric power consumption of 139.6 MW ($P_{C,RG}$) to bring the gases to the desired pressure. The pre-WGS requires 65.3 kg/s at 340 °C and 24 bar and the SEWGS requires 24.72 kg/s of steam at 400 °C and 24 bar (rinse) and 49.44 kg/s of steam at 400 °C and 2.4 bar (purge). The streams specifications at the outlet of the SEWGS section are obtained through the model described in Section 2.1 and are reported in Table 9. To satisfy the steel mill primary energy demand (301 MW), 55.4 kg/s of H_2-rich gas is sent to the steel plant. The remaining H_2-rich is cooled down and treated in the membrane unit which provides the purified hydrogen for the methanol synthesis. The CO_2-rich is cooled down and flashed to separate its water content. The CO_2-dry is partially stored and partially used to produce methanol. The specifications of purified H_2 and CO_2-dry are also reported in Table 9. The methanol distillation process requires 1.5 kg/s of steam at 160 °C and 6 bar for each MeOH module.

$$SPECMeOH = \frac{PEC_{FReSMe} - PEC_{base}}{m_{MeOH}} == \frac{\frac{h_{op}}{f_{el}} \cdot 3600 \cdot \left(P_{net,base} - P_{net,FReSMe}\right) + \dot{m}_{NG} \cdot LHV}{\dot{m}_{MeOH}} \tag{7}$$

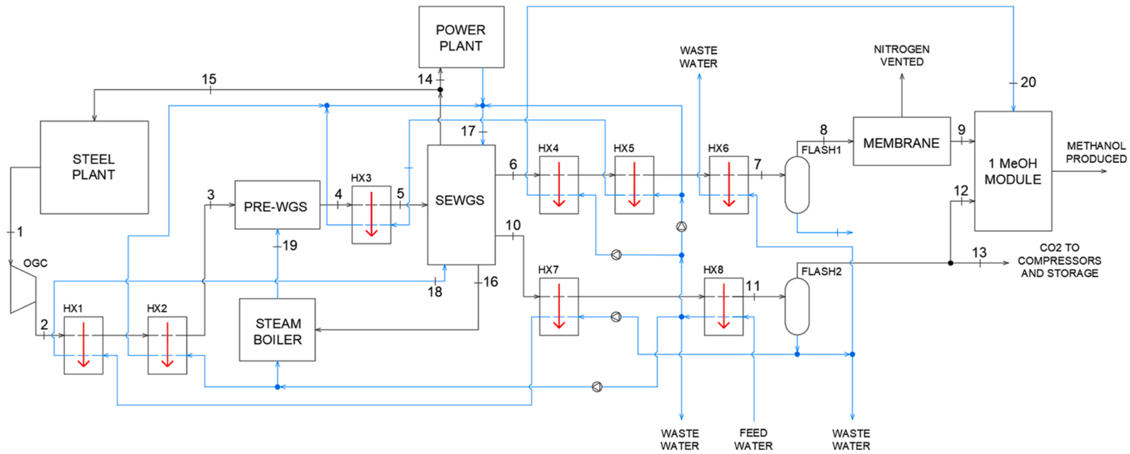

Fig. 2. Schematic plant layout of the FReSMe plant with one methanol module.

Table 10
Main streams specifications for the case with one methanol module.

Stream	Temperature [°C]	Pressure [bar]	Mass flow rate [kg/s]	Molar composition [%mol]				
				H_2O	H_2	CO	CO_2	N_2
1	25	1	289.5	–	4.0	25.6	22.8	47.6
2	467	24	289.5	–	4.0	25.6	22.8	47.6
3	340	24	289.5	–	4.0	25.6	22.8	47.6
4	475	24	354.8	14.5	16.1	5.3	29.7	34.4
5	400	24	354.8	14.5	16.1	5.3	29.7	34.4
6	482	24	18.5	3.4	34.4	2.4	0.8	59.2
7	40	24	18.5	3.4	34.4	2.4	0.8	59.2
8	40	24	18.0	0.3	35.4	2.5	0.8	60.1
9	40	12	0.81	–	99	–	1	–
10	393	1.2	293.2	54.7	0.6	0.1	43.3	1.2
11	30	1.2	293.2	54.7	0.6	0.1	43.3	1.2
12	30	1.2	5.1	3.7	1.3	0.2	92.3	2.6
13	30	1.2	199.4	3.7	1.3	0.2	92.3	2.6
14	482	24	29.7	3.4	34.4	2.4	0.8	59.2
15	482	24	55.4	3.4	34.4	2.4	0.8	59.2
16	482	24	33.7	3.4	34.4	2.4	0.8	59.2
17	400	24	24.7	100	–	–	–	–
18	400	2.4	49.4	100	–	–	–	–
19	340	24	65.3	100	–	–	–	–
20	160	6	1.5	100	–	–	–	–

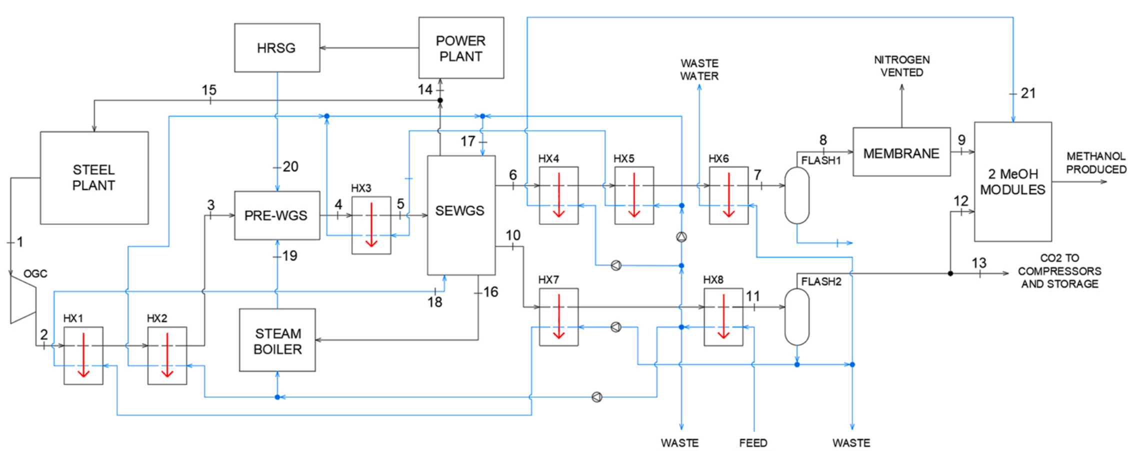

Fig. 3. Schematic plant layout of the FReSMe plant with two methanol modules.

The four streams of steam required by the process are partially produced through heat recovery and partially generated in a boiler fed with H_2-rich gas. Depending on the number of methanol modules, if some H_2-rich is available after covering the steel plant and boiler requirements, it is exploited to produce electricity in the power section.

3.2.1. *One methanol module*

The plant layout in the case with one methanol module is shown in

Table 11
Main streams specifications for the case with two methanol modules.

Stream	Temperature [°C]	Pressure [bar]	Mass flow rate [kg/s]	Molar composition [%mol]				
				H_2O	H_2	CO	CO_2	N_2
1	25	1	289.5	–	4.0	25.6	22.8	47.6
2	467	24	289.5	–	4.0	25.6	22.8	47.6
3	340	24	289.5	–	4.0	25.6	22.8	47.6
4	475	24	354.8	14.5	16.1	5.3	29.7	34.4
5	400	24	354.8	14.5	16.1	5.3	29.7	34.4
6	482	24	37	3.4	34.4	2.4	0.8	59.2
7	40	24	37	3.4	34.4	2.4	0.8	59.2
8	40	24	36	0.3	35.4	2.5	0.8	60.1
9	40	12	1.6	–	99	–	1	–
10	393	1.2	293.2	54.7	0.6	0.1	43.3	1.2
11	30	1.2	293.2	54.7	0.6	0.1	43.3	1.2
12	30	1.2	10.2	3.7	1.3	0.2	92.3	2.6
13	30	1.2	194.3	3.7	1.3	0.2	92.3	2.6
14	482	24	18.9	3.4	34.4	2.4	0.8	59.2
15	482	24	55.4	3.4	34.4	2.4	0.8	59.2
16	482	24	25.9	3.4	34.4	2.4	0.8	59.2
17	400	24	24.7	100	–	–	–	–
18	400	2.4	49.4	100	–	–	–	–
19	340	24	50.3	100	–	–	–	–
20	340	24	15	100	–	–	–	–
21	160	6	3	100	–	–	–	–

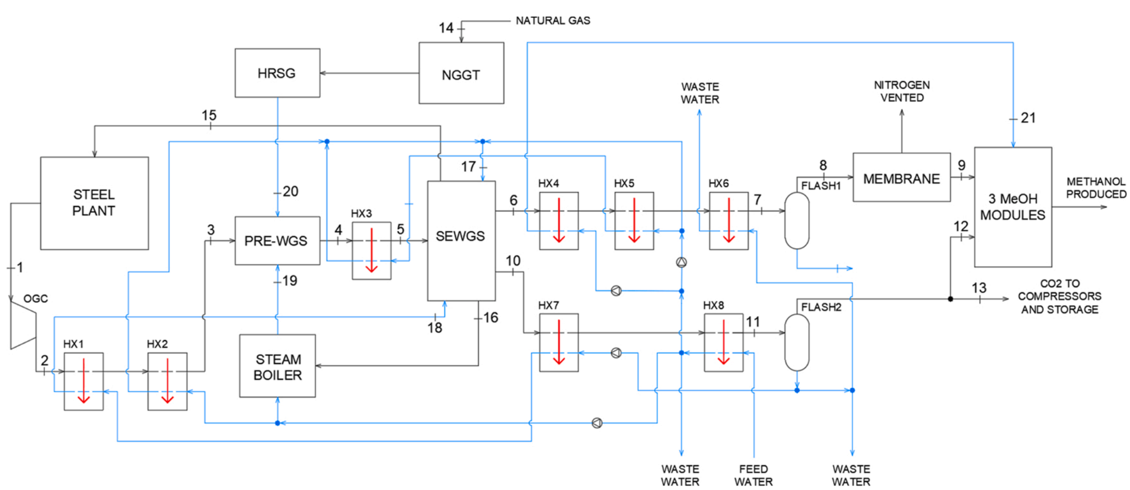

Fig. 4. Schematic plant layout of the FReSMe plant with three methanol modules.

Fig. 2 and the main streams specifications are provided in Table 10.

The methanol synthesis requires 0.81 kg/s of purified hydrogen and 5.1 kg/s of CO_2-dry. In order to provide such hydrogen the membrane is fed with 18.5 kg/s of H_2-rich. The steam required for the pre-WGS is produced in the boiler that consumes 33.7 kg/s of H_2-rich. Considering that 55.4 kg/s of H_2-rich are sent to the steel plant, only 29.7 kg/s of the same gas are available for the power plant. The latter is assumed to be a combined cycle in configuration 1 × 1 operating with an efficiency of 62.4 % [1]. The combined cycle power output is 99.7 MW.

3.2.2. Two methanol modules

The plant layout in the case with two methanol modules is shown in Fig. 3 and the main streams specifications are provided in Table 11.

In this case, the amount of H_2-rich headed for the membrane system is doubled with respect to the case with one methanol module (37 kg/s against 18.5 kg/s). The H_2-rich available for the power plant is only 18.9 kg/s and it is used to feed a gas turbine in simple cycle configuration. The latter is assumed to operate with an efficiency of 42.3 % [1]. By cooling down the hot gases at the outlet of the gas turbine a part of the steam for the pre-WGS`(15 kg/s) can be produced, while the remaining part (50.3 kg/s) is produced in the boiler, that consumes 25.9 kg/s of H_2-rich gas. Both the purge and the rinse are generated through process heat recovery.

3.2.3. Three methanol modules

The plant layout in the case with three methanol modules is shown in Fig. 4 and the main streams specifications are provided in Table 12. As it can be observed, the H_2-rich is not enough the feed both the steam boiler and the power plant, hence it is only exploited in the boiler. Nevertheless, the available amount of H_2-rich is too low for producing the whole amount of steam required by the pre-WGS, hence only 51.23 kg/s are produced in the boiler and the remaining 12.57 kg/s are obtained exploiting the exhaust gases of a dedicated NGGT. The latter consumes 1.3 kg/s of NG and produces 21.45 MW of electric power.

3.2.4. Four methanol modules

When four methanol modules are considered, the heat available from the H_2-rich gas cooling upstream the membrane system covers part of steam necessary for the pre-WGS. As it can be observed in the schematic plant layout shown in Fig. 5, the H_2-rich is divided in three streams: i) 8 kg/s are burned in the steam boiler, ii) 55.5 kg/s are cooled down in the heat exchangers HX4, HX5, and HX6, iii) 18.5 kg/s are cooled down in

Table 12
Main streams specifications for the case with three methanol modules.

Stream	Temperature [°C]	Pressure [bar]	Mass flow rate [kg/s]	Molar composition [%mol]				
				H_2O	H_2	CO	CO_2	N_2
1	25	1	289.5	–	4.0	25.6	22.8	47.6
2	467	24	289.5	–	4.0	25.6	22.8	47.6
3	340	24	289.5	–	4.0	25.6	22.8	47.6
4	475	24	354.8	14.5	16.1	5.3	29.7	34.4
5	400	24	354.8	14.5	16.1	5.3	29.7	34.4
6	482	24	55.5	3.4	34.4	2.4	0.8	59.2
7	40	24	55.5	3.4	34.4	2.4	0.8	59.2
8	40	24	54.0	0.3	35.4	2.5	0.8	60.1
9	40	12	2.4	–	99	–	1	–
10	393	1.2	293.2	54.7	0.6	0.1	43.3	1.2
11	30	1.2	293.2	54.7	0.6	0.1	43.3	1.2
12	30	1.2	15.3	3.7	1.3	0.2	92.3	2.6
13	30	1.2	189.2	3.7	1.3	0.2	92.3	2.6
14	25	1	1.3	see Table 3				
15	482	24	55.4	3.4	34.4	2.4	0.8	59.2
16	482	24	25.9	3.4	34.4	2.4	0.8	59.2
17	400	24	24.7	100	–	–	–	–
18	400	2.4	49.4	100	–	–	–	–
19	340	24	51.2	100	–	–	–	–
20	340	24	12.6	100	–	–	–	–
21	160	6	4.5	100	–	–	–	–

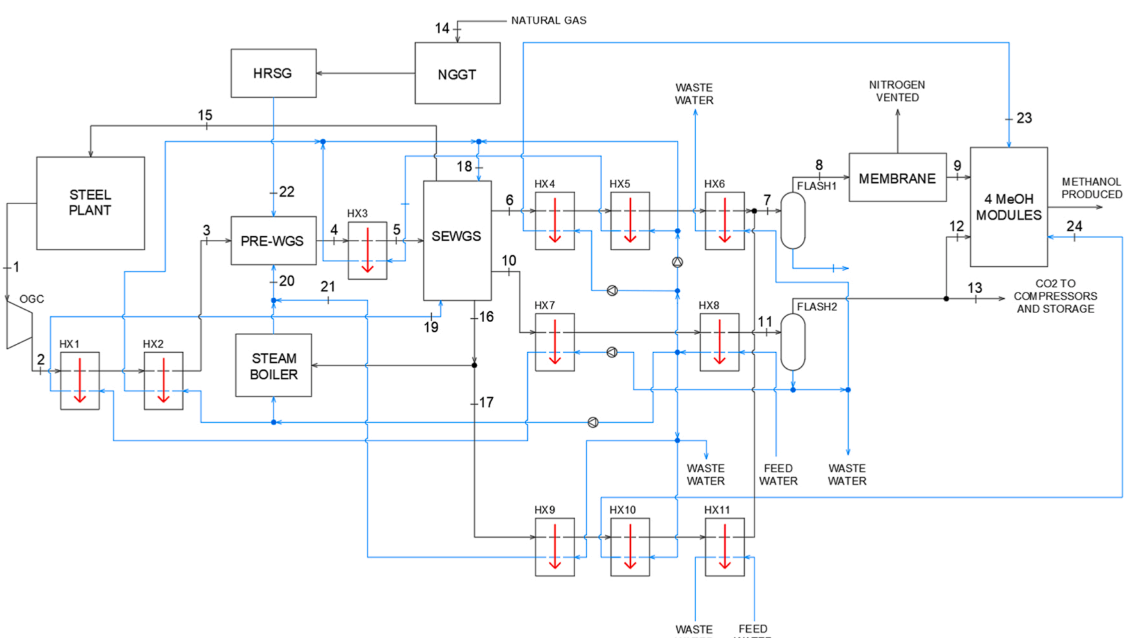

Fig. 5. Schematic plant layout of the FReSMe plant with four methanol modules.

the heat exchangers HX9, HX10, and HX11. Within HX9, 3.8 kg/s of steam for the pre-WGS is generated, while the remaining steam is provided in part by the steam boiler and in part by the HRSG fed with the exhaust gases of the NGGT. The latter consumes 4.7 kg/s of NG and produces 78.6 MW of electric power. The main streams specifications for this case are provided in Table 13.

4. Results

The main results of the energy, environmental, and economic assessment are presented in this section along with four sensitivity analyses aimed to assess the impact of the main assumed parameters on the obtained results.

4.1. Energy and environmental assessment

The energy balances for each investigated plant configuration are reported in Table 14 along with the methanol production capacities, the NG consumed, and the SPECMeOH.

It can be noticed that the highest electricity deficit belongs to the case with three methanol modules, for which 381.8 MW are imported from the grid on average. The configuration with four methanol modules has a lower electricity import thanks to the higher amount of NG consumed in the power production section. The SPECMeOH goes from 144.5 MJ/kg_{MeOH} with one module to 15.7 MJ/kg_{MeOH} with four modules. The SPECMeOH for conventional methanol synthesis from Natural Gas has been provided by the FReSME Project partner CRI and is around 13 MJ/kg_{MeOH}. Therefore, it can be concluded that the methanol production through the FReSMe process has a higher energy intensity than conventional technologies, but this would likely no longer occur for

Table 13
Main streams specifications for the case with four methanol modules.

Stream	Temperature [°C]	Pressure [bar]	Mass flow rate [kg/s]	Molar composition [%mol]				
				H_2O	H_2	CO	CO_2	N_2
1	25	1	289.5	–	4.0	25.6	22.8	47.6
2	467	24	289.5	–	4.0	25.6	22.8	47.6
3	340	24	289.5	–	4.0	25.6	22.8	47.6
4	475	24	354.8	14.5	16.1	5.3	29.7	34.4
5	400	24	354.8	14.5	16.1	5.3	29.7	34.4
6	482	24	55.5	3.4	34.4	2.4	0.8	59.2
7	40	24	74.0	3.4	34.4	2.4	0.8	59.2
8	40	24	72.0	0.3	35.4	2.5	0.8	60.1
9	40	12	3.2	–	99	–	1	–
10	393	1.2	293.2	54.7	0.6	0.1	43.3	1.2
11	30	1.2	293.2	54.7	0.6	0.1	43.3	1.2
12	30	1.2	20.4	3.7	1.3	0.2	92.3	2.6
13	30	1.2	184.1	3.7	1.3	0.2	92.3	2.6
14	25	1	4.7	see Table 3				
15	482	24	55.4	3.4	34.4	2.4	0.8	59.2
16	482	24	26.5	3.4	34.4	2.4	0.8	59.2
17	482	24	18.5	3.4	34.4	2.4	0.8	59.2
18	400	24	24.7	100	–	–	–	–
19	400	2.4	49.4	100	–	–	–	–
20	340	24	19.2	100	–	–	–	–
21	340	24	3.8	100	–	–	–	–
22	340	24	46.1	100	–	–	–	–
23	160	6	4.5	100				
24	160	6	1.5	100				

Table 14
Electric power productions/consumptions for the investigated plant configurations; the average electricity balance accounts for the discrepancy between the operating hours of FReSME plant and steel mill.

	Base case	Ref. case	1 MeOH	2 MeOH	3 MeOH	4 MeOH
P_{GT}			69.9	41.1	–	–
P_{ST}			29.8	–	–	–
$P_{C,RG}$			−139.6	−139.6	−139.6	−139.6
$P_{C,CO2}$			−55.8	−52.1	−48.5	−44.8
P_{NGGT}			–	–	21.4	78.6
P_{memb}			−8.2	−16.3	−24.5	−32.7
P_{MeOH}			−5	−10	−15	−20
P_{net}	234.1	174.3	−108.87	−176.98	−207.74	−164.35
Steel plant el. cons. (MW)	186.7	186.7	186.7	186.7	186.7	186.7
Average overall el. balance (MW)	29.80	−25.4	−288.4	−352.4	−381.8	−342.7
MeOH prod. (t/day)			300	600	900	1200
MeOH prod. (MW)			69.1	138.2	207.3	276.4
NG cons. (kg/s)			–	–	1.3	4.7
NG cons. (MW)			–	–	59.2	217.2
SPECMeOH (MJ/kg_{MeOH})			144.5	72.6	52.3	15.7

Table 15
Specific CO_2 emissions of the integrated steel-FReSMe plant and CO_2 avoidance for each case, compared with the base and reference cases.

	Base case	Ref. case	1 MeOH	2 MeOH	3 MeOH	4 MeOH
Total specific CO_2 emissions (kg_{CO2}/t_{HRC}):						
Steel plant	1112.0	1112.0	479.4	479.4	479.4	479.4
Electricity import	−30.0	25.6	290.5	355.0	384.6	345.2
Power plant	870.0	472.1	26.2	18.6	36.5	96.2
Total emitted	1952.0	1609.8	796.1	853.0	900.5	920.8
CO_2 in methanol			39.8	79.7	119.5	159.3
CO_2 Avoidance (%)	NA	17.5	59.2	56.3	53.9	52.8

higher methanol production capacities than the considered ones. The specific carbon dioxide emissions of the integrated FReSMe-steel plant are reported in Table 15 along with those obtained for the base and reference cases. The CO_2 avoidance achieved by the FReSMe system ranges between 52.8 % and 59.2 % which is significantly higher than the value obtained for the reference case (17.5 %). The highest value of CO_2 avoidance is achieved with one methanol module. Hence, it can be stated that the application of the FReSME technology to integrated steel plant allows to mitigate the steel-making process emissions in a much more affective way than conventional post-combustion technologies applied to the power generation section. It is also interesting to notice that the FReSMe process allows to avoid more emissions than the SEWGS applied for the steel plant decarbonization as described in the previous work [1]. In the latter, the SEWGS was used as pre-combustion carbon capture technology to treat the steelworks arising gases headed for the power production; a CO_2 avoidance of 38 % was calculated against the 53 %–59 % obtained in this study for the FReSMe system.

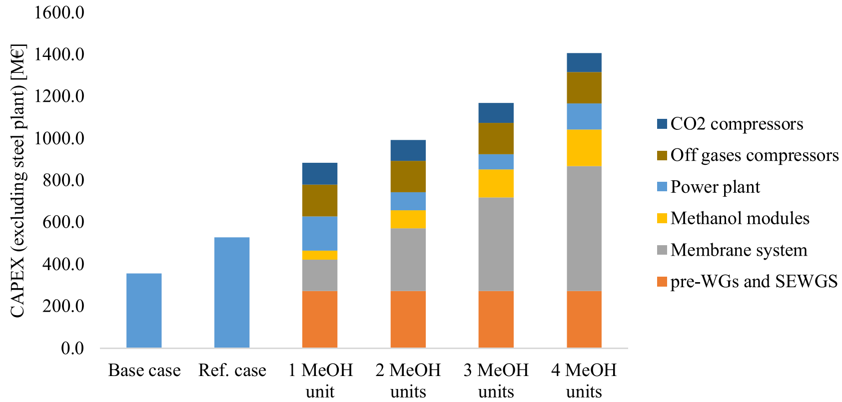

Fig. 6. CAPEX of each case (all the costs include installation, indirect, contingency, and owner's costs).

Table 16
Main results of the techno-economic assessment for the different investigated cases.

	Base case	Ref. case	1 MeOH	2 MeOH	3 MeOH	4 MeOH
CAPEX (M€)	4945.1	5118.7	5472.4	5582.7	5758.5	5995.9
OPEX (M€/ year)	1396.1	1407.7	1572.4	1593.7	1617.4	1640.6
LCOHRC (€/t_{HRC})	475.9	485.2	522.9	520.9	521.5	523.6
LCOM (€/t_{MeOH})	–	–	1037.6	685.3	600.7	574.1
CCA (€/t_{CO2})	–	27.8	40.6	40.9	43.3	46.2

4.2. Economic assessment

The different costs contributing to the CAPEX of the different FReSME cases are reported in Fig. 6, where the steel plant capital cost, not shown for the sake of clarity, is equal for all the cases (4590.2 M€). The comparison between the different configurations highlights that the CAPEX of the integrated steel-FReSMe plant is generally higher than those of the base and reference case, and it increases with the methanol production capacity. With one methanol module the main capital cost is represented by pre-WGS and SEWGS while the membrane system becomes the main cost driver when more modules are considered. A detailed overview of the different costs that contribute to the CAPEX of each plant configuration is provided by Table A1.

The overall CAPEX of each analysed case is reported in Table 16 along with OPEX, LCOHRC, LCOM and CCA. The table points out that: i) the LCOHRC is comparable for all of the FReSMe cases and ranges between 520.9 €/t_{HRC} and 523.6 €/t_{HRC}: the lowest value is achieved by the configuration with two modules and is 9.4 % higher than the base case value; ii) the LCOM is in the range 574.1 €/t_{MeOH} – 1037.6 €/t_{MeOH} and it decreases with the methanol production capacity; iii) the CCA of the reference case is 27.8 €/t_{CO2} while for the FReSMe cases it ranges from 40.6 €/t_{CO2} to 46.2 €/t_{CO2}; the lowest value belongs to the configuration with one methanol module which is also the one with the highest CO_2 avoidance. It is important to highlight that despite the LCOHRC and the CCA are higher for the FReSMe than for the reference case, the remarkably higher CO_2 reduction achieved with the FReSMe process makes this technology a promising solution for the near future steel production. Indeed, for carbon taxes above 40.6 €/t_{CO2}, which are currently (April 2021) implemented in several European countries (e.g. France, Finland, Liechtenstein, Norway, Sweden, and Switzerland) [29], the FReSMe process ensures a higher economic profitability than both the base and the reference cases.

The LCOHRC obtained for the FReSMe cases is higher than the considered HRC market price, however in the future higher HRC market prices could be achieved if the steel industry moves toward the decarbonization. Another interesting consideration arises from the obtained values of LCOM, which are significantly higher than the current European market price for methanol. The reason behind such a high cost is that the LCOM is obtained assuming that the HRC is sold at its market price (lower than the LCOHRC), hence the methanol must be sold at relatively high prices in order to break-even after 25 years. Though, it is necessary to notice that: i) lower LCOM can be obtained if higher HRC selling prices are considered (see sensitivity analysis in Subsection 4.3.3), ii) higher methanol selling prices may be reached in the future if the methanol production industry is affected by CO_2 emissions mitigation policies.

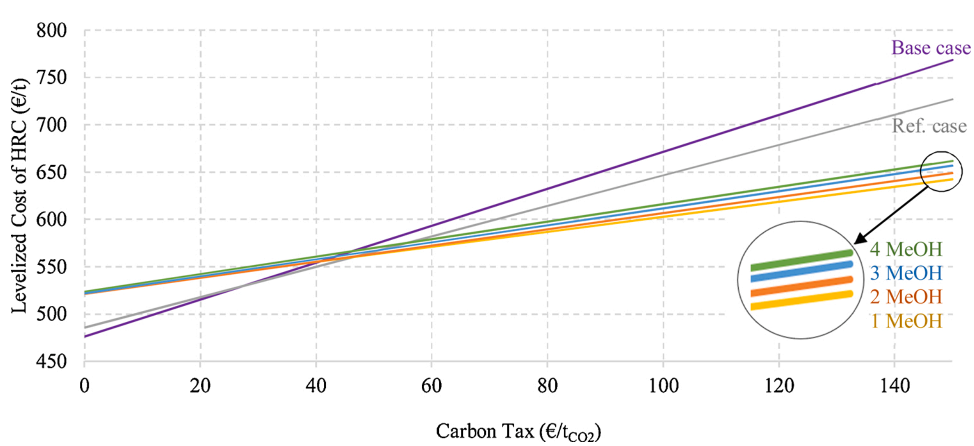

Fig. 7. Effect of the carbon tax on the LCOHRC.

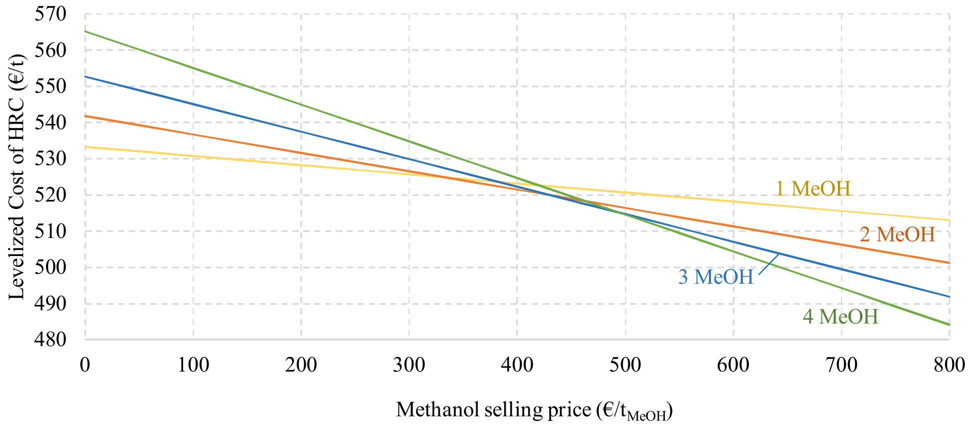

Fig. 8. Effect of the methanol selling price on the LCOHRC.

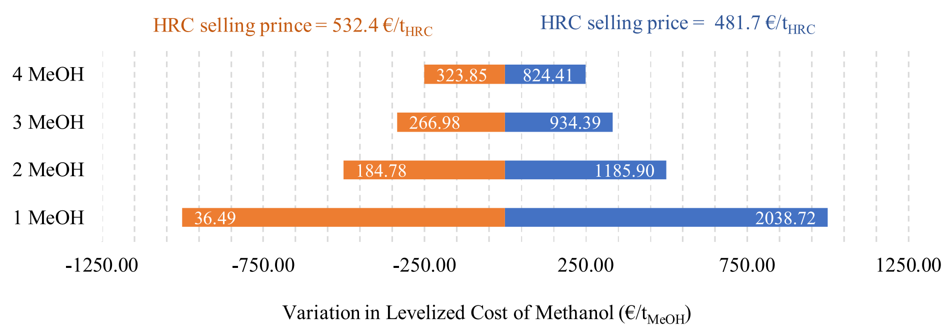

Fig. 9. Effect of the HRC selling price on the LCOM; the bars show the variation of LCOM with respect to baseline case, the labels indicate the absolute values of LCOM.

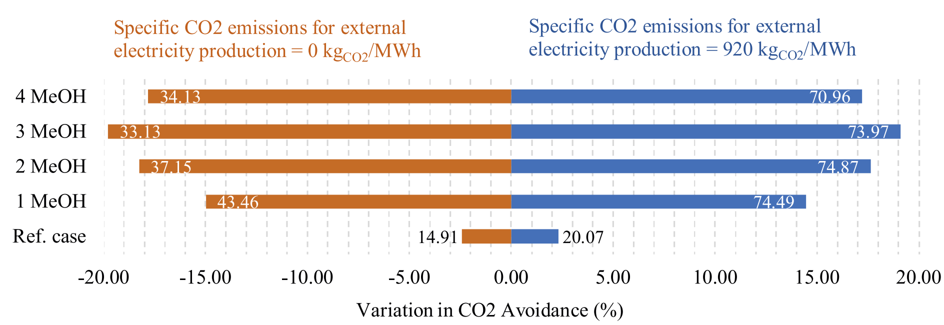

Fig. 10. Effect of the energy mix on CO_2 avoidance; the bars show the variation of CO_2 avoidance with respect to baseline case, the labels indicate the absolute values of CO_2 avoidance.

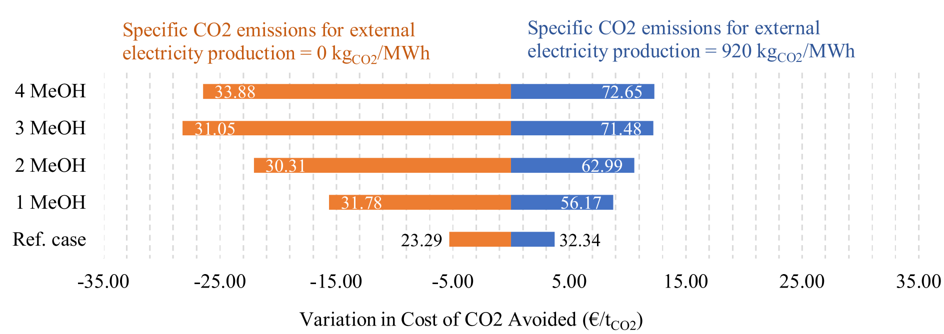

Fig. 11. Effect of the energy mix on CCA; the bars show the variation of CCA with respect to baseline case, the labels indicate the absolute values of CCA.

4.3. Sensitivity analyses

Four sensitivity analyses are presented in this section to assess the impact of carbon tax, methanol selling price, HRC selling price, and CO_2 emissions for external electricity production on the costs and performances of the investigated plant configurations.

4.3.1. Effect of carbon tax

The effect of carbon tax on the economics of the investigated configurations is assessed varying the carbon tax from zero (baseline scenario) to 150 €/t_{CO2}. The resulting values of LCOHRC are reported in Fig. 7.

As expected from the CCA values obtained for the FReSMe cases, when a carbon tax higher than 46.2 €/t_{CO2} is considered, the FReSMe process has a higher economic profitability than the base and reference cases in all the investigated configurations. For carbon tax rates higher than 40.6 €/t_{CO2} the configuration with one methanol module has the lowest LCOHRC if compared to the other cases. Hence, despite the optimal plant configuration has two methanol modules when no carbon tax is considered (see Table 16), the configuration with one module appears the optimal one for carbon tax rates higher than 40.6 €/t_{CO2}. Since for lower carbon tax rates the FReSMe is not competitive, the configuration with one module is generally recommended to enhance the economic profitability of the process. With a carbon tax of 150 €/t_{CO2} the FReSMe with one MeOH module is characterized by a LCOHRC of 642.3 €/t_{HRC}, 11.6 % lower than the reference case and 16.5 % lower than the base case.

4.3.2. Effect of methanol selling price

In order to investigate the effect of the methanol selling price, the latter is varied from zero to 800 €/t_{MeOH} and the resulting LCOHRC for each configuration is reported in Fig. 8.

As it can be noticed, when the methanol is given away for free the highest economic profitability is achieved with one methanol production module. On the contrary, if a selling price of 800 €/t_{MeOH} is assumed the lowest LCOHRC belongs to the case with four methanol modules and is 484.1 €/t_{HRC}. In detail, the optimal number of methanol modules is: i) one for a methanol selling price lower than 330 €/t_{MeOH}; ii) two for prices between 330 €/t_{MeOH} and 430 €/t_{MeOH}; iii) three for prices in the range 430–500 €/t_{MeOH}, iv) four for prices higher than 500 €/t_{MeOH}.

4.3.3. Effect of the HRC selling price

The impact of the HRC selling price on the integrated steel-FReSMe plant economics is assessed varying the HRC selling price and evaluating the resulting LCOM. The results presented in Fig. 9 are obtained considering a variation of +/- 5% around the initially-assumed value (507 €/t). First of all, it can be noticed how such a small variation of HRC selling price leads to substantial variations in LCOM (from +/- 43 % to +/- 97 %). The highest sensitivity belongs the case with one methanol unit. An increase in the methanol production capacity leads to a decrease of the plant economics vulnerability to the HRC selling price fluctuations.

When a HRC selling price of 532.4 €/t is considered, the LCOM reaches, for all of the cases, values lower than the current methanol selling price; the lowest value is achieved with one methanol module and is 36.5 €/t. If 481.7 €/t is assumed as HRC selling price, the lowest LCOM belongs to the case with four methanol modules and is 824.4 €/t.

4.3.4. Effect of energy mix

Another sensitivity analysis is performed to assess the impact of the energy mix on CO_2 avoidance and cost of CO_2 avoided of the different FReSMe layouts. This analysis is carried out varying the specific CO_2 emissions for external electricity production from zero to the double of the originally-assumed value, hence 920 kg_{CO2}/MWh. The HRC and methanol selling prices are set equal to the baseline values. The results in terms of CO_2 avoidance variation are shown in Fig. 10 while those related to the cost of the CO_2 avoided are reported in Fig. 11. It can be noticed that the highest sensitivity belongs to the case with three methanol modules which is the one with the highest electricity import. When a highly carbon-intensive energy mix is considered (920 kg_{CO2}/MWh) the highest CO_2 avoidance is no longer achieved with one methanol module, but it belongs to the case with two modules (74.9 %); on the contrary, the lowest CCA is still achieved with one module (56.2 €/t_{CO2}). In case of perfectly carbon-free energy mix, the highest CO_2 avoidance and the lowest CCA among the FReSMe cases belong to the configurations with one and two methanol modules, respectively.

5. Conclusions

This work discusses a techno-economic assessment of the FReSMe process when integrated with steel plants for CO_2 emissions mitigation and methanol production. The analysis is focused on the integration of the methanol synthesis with the steel plant power section considering different methanol production capacities. The latter is varied considering one, two, three, and four modules for the methanol synthesis, each with a nominal capacity of 300 t/day. For each investigated plant configuration costs and performances are assessed and compared to those of two reference cases. The former (base case), involves a conventional steel plant with integrated power production; in the latter (reference case), amine based post-combustion CO_2 capture is included in the power production section. Detailed mass and energy balances show that the application of the FReSMe technology to steel plants allows to reach CO_2 avoidance values ranging from 53 % to 59 % against the 17.5 % obtained for the reference case. The highest CO_2 reduction is achieved with one methanol module as it has the lowest amount of electricity supplied from the grid or natural gas. Indeed, when the methanol production increases the amount of hydrogen-rich gas available for the power production decreases and this leads to a higher amount of electricity that must be imported from the grid or produced from natural gas. The techno-economic analysis points out that, when no carbon tax is considered, the Levelized Cost of Hot Rolled Coil (LCOHRC) for the FReSMe configurations ranges between 520.9 €/t_{HRC} and 523.6 €/t_{HRC}: the lowest value is achieved with two methanol modules and is 9.4 % higher than the value calculated for a conventional steel mill without carbon capture. Hence, if the LCOHRC is considered as main indicator for the plant techno-economic profitability, the optimal configuration for the FReSMe system in case of no carbon tax is with two methanol units. The Cost of CO_2 Avoided is in the range 40.6 €/t_{CO2} – 46.2 €/t_{CO2}; the lowest value is achieved with one methanol module, which is the one with the highest CO_2 avoidance. Despite a lower CCA is obtained for the reference case (27.8 €/t_{CO2}), the potential of the FReSMe process remains remarkable thanks to its higher emissions reduction capability. Indeed, with a carbon tax above 40.6 €/t_{CO2}, the FReSMe system ensures a higher economic profitability than both the base and the reference cases. Moreover, for carbon tax rates above these values the optimal FReSMe configuration has no longer two methanol modules, but one single module. The sensitivity analyses on the HRC and methanol selling prices show that both the prices have a remarkable effect on the plant profitability: on one hand, the HRC selling price has much more impact than the methanol one; on the other hand, the methanol selling price is a crucial parameter for the determination of the optimal methanol production capacity. The sensitivity analysis on the energy mix demonstrates that even for perfectly carbon-free or extremely carbon intensive energy mixes the CO_2 avoidance is higher than the one obtained with amine-based carbon capture.

In conclusion, with a carbon tax rate above 40.6 €/t_{CO2}, the FReSMe process ensures higher CO_2 emissions reduction and lower costs than conventional carbon capture systems based on post-combustion in the power section. Since such rate has been already overcome in several European countries and the carbon tax is expected to increase in the near future, the FReSMe process can represent an effective and economically-attractive solution for the steel industry decarbonization. Future works may focus on the overall optimization of the integrated system composed by steel plant, SEWGS, methanol plant, and power section.

Data availability

Data will be made available on request.

Author statement

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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.

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Appendix A

Table A1
Detail of the different costs contributing to the plant CAPEX.

Components Capital Costs (M€)	Base case	Ref. case	1 MeOH unit	2 MeOH units	3 MeOH units	4 MeOH units
Steel Plant	4590.2	4590.2	4590.2	4590.2	4590.2	4590.2
pre-WGS			2.2	2.2	2.2	2.2
SEWGS			271.0	271.0	271.0	271.0
Membrane system			148.5	297.0	445.5	594.0
Methanol modules			43.9	87.8	131.7	175.6
H2-rich GTs			83.3	65.6		
HRSC			60.2			
NGGT					47.2	84.8
HRSG for NGGT					5.3	19.5
Boiler			3.6	2.8	2.9	0.9
Off gases compressors			151.3	151.3	151.3	151.3
CO2 compressors			102.4	97.8	93.2	88.4
Heat Exchangers, pumps, and SEP.			15.7	16.9	18.0	18.0
Power plant for base/ref. cases	354.9	528.5				
Overall CAPEX	4945.1	5118.7	5472.4	5582.7	5758.5	5995.9

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