Fuelling power plants by natural gas: An analysis of energy efficiency, economical aspects and environmental footprint based on detailed process simulation of the whole carbon capture and storage system

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ABSTRACT

In view of the low-carbon transformation of the power sector, natural gas-fired power generation is the only technology, among fossil resources, that will continue to provide an important source of flexibility for the power system in the coming years. However, the carbon dioxide emissions produced by the operation of such plants call for carbon capture and storage equipment, whose deployment needs to be assessed and compared with the main renewable technologies: wind power and photovoltaics. This work uses process simulation in order to assess two different carbon capture processes: a traditional one, based on monoethanolamine, and an innovative one, based on hot potassium carbonate. Process simulation is also used for the transportation of carbon dioxide to the sequestration site. Mass and energy balances from the simulations are then used for the calculation of the Energy Return on Energy Invested, the Levelized Cost of Energy and as inputs for the Life Cycle Assessments of both alternative designs. The life cycle analyses of the considered power technologies exhibited higher contributions due to fossil-based power plants towards climate-related impact categories, while renewable sources were revealed to be more burdensome for the exploitation of mineral resources. The calculated Energy Return on Energy Invested for gas-fired power plants with carbon capture and storage is between 5.2 and 12.4, comparable with the values of photovoltaics and wind power. On the other hand, their Levelized Cost of Energy is between 10.2 and 20.0 eurocent per kilowatt-hour, much higher than that of renewables. The conclusion is that, at present, the sustainability of gas-fired power stations equipped with carbon capture and storage should be carefully considered and not taken for granted.

1. Introduction

After two years of growth, global emissions were unchanged in 2019 even though the world economy has grown by 2.9% [1], primarily thanks to the expansion of renewable sources in the power sector. Nevertheless, still about 80% of global carbon dioxide (CO_2) emissions originate from the energy sector [2]. In this respect, gas-fired power generation is the third largest source of CO_2 emissions, accounting for 7.1 Gt in 2018 [3], more or less a quarter of the total emitted by the energy sector [4]. Since the increasing share of variable generation of photovoltaics and wind power needs to be followed by an increase in the flexibility of the power system to balance supply and demand, the future share of gas-fired power plants seems to remain important, as shown in Table 1 [4]. Therefore, in order to reduce the CO_2 emissions of gas-fired plants, a number of them could be retrofitted with Carbon Capture and Storage (CCS). Nonetheless, this technology has not been successfully implemented on a large scale yet.

According to the state of the art, research on CCS and its application to power plants has been prolific over the last decade, with a stable rate of 90–100 documents published per year [5]. The physical properties impacts on CCS processes are well described in [6]. Numerous studies in the literature carried out detailed assessments of CCS processes, based on results from process simulations [7]. For example, several works

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Nomenclature

Abbreviations

CCS	Carbon Capture and Storage
CC-T	Climate Change - Total
CF	Capacity Factor
CW	Cooling Water
DPR	Dual Pressure Regeneration
EF	Environmental Footprint
EGR	Exhaust Gas Recirculation
ELCA	Energy Life Cycle Assessment
ELECNRTL	ELECtrolyte Non-Random Two-Liquid
EoS	Equation of State
EQ-EF	Ecosystem Quality - Eutrophication Freshwater
EQ-EM	Ecosystem Quality - Eutrophication Marine
EQ-ET	Ecosystem Quality - Eutrophication Terrestrial
EQ-FE	Ecosystem Quality - Freshwater Ecotoxicity
EQ-FTA	Ecosystem Quality - Freshwater and Terrestrial Acidification
EROC	Energy Return on Carbon
EROEI	Energy Return On Energy Invested
ERR	Energy Return Ratio
FG	Flue Gases
FO&MC	Fixed Operation and Maintenance Costs
GHG	GreenHouse Gas
HH-CE	Human Health - Carcinogenic Effects
HH-IR	Human Health - Ionizing Radiation
HH-NCE	Human Health - Non-Carcinogenic Effects
HH-OD	Human Health - Ozone Layer Depletion
HH-PCOC	Human Health - Photochemical Ozone Creation
HH-RE	Human Health - Respiratory Effects
HP	High Pressure
HPC	Hot Potassium Carbonate
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Energy
LP	Low Pressure
MEA	MonoEthanolAmine
NEA	Net Energy Analysis
NEG	Net Energy Gain
NER	Net Energy Ratio
NGCC	Natural Gas Combined Cycle
P_{inst}	Installed Capacity
PR-BM	Peng-Robinson equation of state with Boston-Mathias modifications
PS	Process Simulation
PV	Photovoltaics
RD-F	Resources Depletion – Fossil Fuels
RD-L	Resource Depletion - Land Use
RD-M	Resource Depletion - Minerals and Metals
RD-W	Resources Depletion - Dissipated Water
SGTC	Sequential Gas Turbine Combustion
$S_{o\&m}$	Share of investment costs due to operation and maintenance
TPC	Total Plant Cost
VO&MC	Variable Operation and Maintenance Costs
W	Wind

Parameters

C_{ef}	Carbon emission factor
cf	capacity factor
CRF	Capital Recovery Factor
$FO\&MC$	Fixed Operation Costs
i	interest rate
L	plant lifetime
OC	Overnight Cost
P	net power output
$s_{o\&m}$	share of the investment costs dedicated to operation and maintenance
TPC	Total Plant Cost
$VO\&MC$	Variable Operation Costs
ε	embodied energy of capital per installed unit of power produced
ε_c	proportionality coefficient between costs of energy and capital costs
η	global efficiency of the energy production plant

Subscripts

E	Energy
cap	capital
f	fuels
in	inlet
o&m	operation and maintenance
out	outlet
th	thermal
EROEI	Energy Return On Energy Invested
EXT	Extended
fuel	fuel at point of use
SOC	Societal
ST	Standard
LCOE	Levelized Cost Of Energy
CCS	Carbon Capture and Storage

evaluated the performance of chemical absorption with MonoEthanolAmine (MEA, C_2H_7NO) and membrane-based CCS, concluding that the former is more energy-intensive and generates higher environmental impacts [8]. Despite its apparent advantages, however, membrane-based CCS [9] is still at the development stage, while chemical absorption has an advanced technological maturity. Recently, the use of hot potassium carbonate (HPC, K_2CO_3) has attracted attention as a possible alternative solvent, characterized by higher stability, low toxicity, non-volatility, and the same technology readiness as MEA [10]. Most of the works are focused on the assessment of CCS technology coupled with coal-based power plants [11]. However, to reflect the current situation and the strategic plans towards a smooth energetic transition (future trends reveal that coal will cover only 2% of the peak demand, while natural gas will cover 26%, as shown in Table 1), natural gas-fired plants need also to be analysed, since they are characterized by higher and more diluted flue gases (FG) flow rates. To the best of the

Table 1
Sources of flexibility in Europe expressed as a percentage of the peak demand (*i.e.*, the load power).

Year	Hydro	Natural Gas	Coal	Oil	Nuclear	Other	Interconnections	Batteries	Demand Response
2018	28%	27%	13%	5%	7%	2%	12%	1%	5%
2040	18%	26%	2%	2%	4%	2%	35%	5%	6%

authors' knowledge, no studies on HPC-based CCS applied to gas-fired plants are present in the literature. In addition, most of the works do not address the problem from a thorough and interdisciplinary approach that evaluates energetic, economic and environmental factors based on rigorous and coherent material and energy balances and costs data, but rather focus on the analysis of single aspects.

For these reasons, the aim of the present work is to analyse and assess the sustainability of natural gas-fired power plants without and with a CCS system, by combining detailed process simulation (PS) with an evaluation of the Energy Return on Energy Invested (EROEI), the Levelized Cost of Energy (LCOE) and the Life Cycle Assessment (LCA). The results obtained are then compared using the same metrics as are used for photovoltaics and wind power.

All the data needed to evaluate the EROEIs, LCOEs and LCAs are provided by PS, with material and energy balances calculated using reliable and validated models, taking as references existing processes coupled with an existing real natural gas power generation plant. Process simulation is a mature tool that solves material and energy balances for chemical [12] and biochemical [13] processes: its use is consolidated in the phase of process design, optimization, and feasibility studies. Indeed, the outcomes of the desired process must be evaluated in terms of energy consumption, the cost of energy and emission of greenhouse and pollutant gases to limit the industrial environmental impact. Moreover, PS can provide an energetic and an economic evaluation of the given process, as well as sensitivity analysis of the most relevant independent variables of the process itself. By combining PS with EROEI estimation, LCOE calculation and the LCA procedure, it is possible to obtain target values for all the desired indicators and impact categories. In this way, process engineers can evaluate the sustainability of the proposed design at an early stage using a rigorous process simulation-based analysis [14].

With reference to the energetic aspect, the appropriate calculation of the EROEI [15] serves as a reasonable proxy for the biophysical utility of any particular energy source to society [16]. However, EROEI values vary considerably from study to study depending on the data used for the estimation of the energy contributions involved [17] and of the EROEI of fuels [18]. Recent studies calculated the value of the EROEI when a CCS technology is coupled to electrical energy production processes from fossil fuels [19], highlighting all the necessary data for a reliable estimation of the effect of CCS on the EROEI [20].

As far as the environment is concerned, considerable effort has been spent on evaluating the impacts related to electricity production. A review of the life cycle of renewable energy sources [21] and a specific one on electricity generation [22] are available in the literature. Regarding life cycle assessments of CCS, early works dealt with the emission from the MEA capture process [23] and with the installation of MEA capture plant in series at a natural gas combined cycle power plant [24] or a pulverized coal-fired power plant [25]. LCA studies now envisage other promising technologies within their scopes [26], *e.g.* separation membrane [9], oxy-fuels [27], alternative solvents [28], power supply [29] and fuels [30], or chemical looping configurations based on pre-combustion [31] or post-combustion [32] carbon capture, aiming at identifying the best technology for future industrial applications. Among the most investigated CCS technologies, the comparison between MEA and HPC has already been studied from the LCA standpoint. Process simulation tools have been used to obtain life cycle inventories of each carbon capture process in terms of mass and energy balances, but for coal-fired power plants only. Many papers have used AspenPlus™ as process simulation software. Zhang et al. modelled different post-combustion technologies, *i.e.,* an MEA-based system, a gas separation membrane process and a hybrid membrane-cryogenic process [8]. Urech et al. compared three solvents (monodiethanolamine, hot potassium carbonate and Selexol™) for a pre-combustion carbon capture application [33]. Wang et al. combined MEA-based process simulation with power plant steam cycles obtained using Cycle-Tempo software [29]. Grant et al. compared post-combustion carbon capture using either hot potassium carbonate or MEA [34]. Besides AspenPlus™, another software called Pro Treat® has been employed for comparing potassium carbonate (bio-catalyzed and traditional) and amine-based carbon capture technologies [35]. Most of these simulations do not take into consideration the shared infrastructures and operations (*i.e.,* transportation and storage of CO_2), preventing the comparison of their results with other electricity generation technologies. A number of publications compare coal-fired or natural gas-fired power plants equipped with carbon capture systems to other electricity generation sources. For instance, Turconi et al. reviewed the existing LCA studies dealing with hard coal, lignite, natural gas, oil, nuclear power, hydropower, photovoltaics, wind and biomass in order to identify the averaged environmental impacts of each technology [36]. Hertwick et al. performed a comparative LCA study, including several photovoltaics technologies, concentrating solar power, hydropower from different reservoirs, wind power onshore and offshore, various coal and natural gas technologies with and without CCS [37]. Gibon et al. combined existing data for coal, natural gas, ground-mounted and roof-mounted photovoltaics, concentrating solar power, hydropower, geothermal and wind power with original life cycle inventories covering biopower technologies with and without CCS and nuclear power [38]. In general, these works show a general increase of the environmental footprints for traditional technologies in the majority of impact categories. However, none of these works compare complete CCS systems employing different technologies, as well as fossil- and renewables-based power generation technologies. The method proposed in this paper aims to fill this gap, using detailed process simulations to provide a comprehensive cradle-to-gate LCA study of a traditional natural gas-fired power plant without and with two CCS technologies (MEA and HPC), a photovoltaic plant and a wind turbines system.

In addition, also the few relevant scientific papers discussing economic aspects focus on coal-fired plants [39], and often consider a small nominal net power output related in most cases to pilot plants [40]. Moreover, the technical reports available in the literature usually do not consider the CCS option [41] or they do not include the transportation and storage of CO_2. With the method proposed in this work, the total plant cost obtained from the PS is directly used as a key input for the calculation of the LCOE.

With respect to the state of the art, the main advance of this paper is the use of detailed process simulation of CCS processes tailored to a real Natural Gas Combined Cycle (NGCC) plant, taken as representative of electrical energy production from natural gas. AspenPlus™ is employed for comparing two CO_2 capture processes: (i) a traditional one, well known in the petrochemical industry, based on MEA and (ii) an innovative one based on HPC. In both cases, a simulation of the transport and preparation for storage of CO_2 is also evaluated. Accordingly, the novelty of this paper is twofold: on the one hand, this is the first time a novel process for CCS based on HPC is simulated and optimized in order to predict the possibility of coupling it with a real NGCC power plant. On the other hand, this paper shows how process simulation results in terms of mass balance, energy balance and equipment cost evaluation can be successfully used for the *a priori* estimation of relevant indicators such as the EROEI, LCOE and LCA, which could also be valuable for defining long-term strategies for the development of national and international energy systems.

The paper is organized as follows: section 2 presents the methods used in this paper including the details of the process simulation, the calculation of the EROEI, LCOE and LCA; section 3 provides and discusses in detail the results obtained with the methods previously described; lastly, some final considerations are reported in section 4.

2. Methods

In this section, the description of the natural gas power station, the methods utilized in the CCS process simulations and in the subsequent evaluation of the EROEI, LCOE and LCA indicators are reported.

2.1. Electrical energy production from natural gas

Thermal power stations using gas turbines are widely used worldwide because they are simple, cheap and represent a reliable source of flexibility. The most common configuration includes a compressor, a combustion chamber, and a gas turbine. The compressed air enters one or more combustion chambers where it is mixed with the fuel, producing combustion gases that are sent to the gas turbine, where they expand. This expansion provides the power needed to drive the synchronous generator used for the production of electricity.

NGCCs power plants use the high-temperature exhaust gases, or FG, from one or more gas turbines, to generate steam that is then exploited to drive a steam turbine generator [42]. This combination of gas and steam power plant brings the overall efficiency from a value typically less than 30% for the gas turbine alone, up to 60% when also the steam turbine is employed [43].

The rigorous simulation of an NGCC is not the focus of this work. Data related to the material and energy balances necessary for the calculation of the EROEI, LCOE and LCA were extracted from detailed studies taken from the literature [20]. In particular, the characteristics of the FG of the power plant that were used as input for the CCS process simulations were taken from a report of the National Energy Technology Laboratory of the U.S. Department of Energy [44]. According to this source, an NGCC power plant with an input flow rate of 75901 kg/hr of natural gas and an installed capacity of 564.7 MW_e (P_{inst}), equivalent to a 555.1 MW_e net power output (P), was taken as a suitable reference for a typical gas power station. Such a power plant generates roughly 900 kg/s of FG, available from the stack at 143 °C and 1 bar, with the composition reported in Table 2.

The FG composition is in agreement with that reported in other studies [45]. In fact, NGCC power plants are characterized by the production of a large FG flow rate, with low CO_2 (3–4 mol%) and high O_2 (11–12 mol%) contents, due to the large excess of air needed to keep the temperature below allowable values in the combustor. For this reason, technological modifications of the power plant, such as Exhaust Gas Recirculation (EGR), Sequential Gas Turbine Combustion (SGTC), and others, are being investigated to increase the CO_2 content and facilitate the subsequent capture step [46]. However, because these solutions are still at the development stages, they are not considered in this work. Data from Table 2 are used as the input stream to the CCS processes of interest.

2.2. Carbon capture and storage process simulation

The process simulations of carbon capture by means of aqueous solutions of MEA or HPC, and of the subsequent transport/storage were carried out by means of Aspen Plus™ v.11. The following paragraphs detail the thermodynamic models used, as well as the process flowsheets implemented.

2.2.1. Thermodynamic and kinetic models

The ELECtrolyte Non-Random Two-Liquid (ELECNRTL) thermodynamic model was selected to evaluate the properties of the aqueous systems considered. ELECNRTL was developed to account for the non-ideality of a single salt that completely dissociates in water, and it has been widely adopted and validated for CO_2 absorption/stripping applications using both MEA [47] and HPC solvents [10]. Detailed information about the chemical reactions occurring in MEA and HPC solutions are reported in the Supplementary Material. For all the absorption/stripping columns, a rigorous rate-based modelling approach, accounting for mass-transfer and appropriate sizing to ensure a correct fluid-dynamic regime, was employed.

On the other hand, to model CO_2 compression and pipeline transport, the Peng-Robinson (PR) Equation of State (EoS) with Boston-Mathias modifications (PR-BM) was selected. Diamantonis et al. [48] have shown that the PR EOS is able to describe the behaviour of pure CO_2 as well as of binary/ternary mixtures comprising most typical impurities, such as nitrogen (N_2) and oxygen (O_2), provided that suitable binary interaction parameters (k_{ij}s) are employed. The validity of the Aspen Plus™ PR-BM model in the near supercritical region against experimental data for pure CO_2 [49], for binary CO_2-N_2 [50] and CO_2-O_2 mixtures [51], and for the ternary CO_2-N_2-O_2 system [52] was verified. It is commonly acknowledged that, to minimize the energy costs, CO_2 should be transported at a pressure above the critical value P_c (73.8 bar), in order to have low viscosity and high density [53]. The presence of impurities causes the mixture properties to be different from those of pure CO_2. In particular, a phase envelope can be identified depending on the composition, so that sufficiently high pressures should be kept along the pipeline to avoid the formation of a 2-phase system [54]. In this work, it was verified that no retrograde condensation phenomena occur under the conditions investigated.

Table 2
Characteristics of the flue gases from the NGCC power plant [44].

Parameter	
Flow rate (kg/s)	897.4
Temperature (°C)	143
Pressure (bar)	1
Molar composition (%)	
CO_2	4.04
N_2	74.32
O_2	12.09
H_2O	8.67
Ar	0.88

2.2.2. Process schemes

The process flow diagram of carbon capture from flue gases using an MEA solution developed in Aspen Plus™ is shown in Fig. 1.

The FG coming from the stack (P = 1 bar, T = 143 °C) is cooled first in the gas/gas heat exchanger E-101 by the clean gas from the top of the absorber, and then to a T = 35 °C in E-102 by using cooling water (CW). The FG stream, after increasing its pressure to 1.23 bar in the blower B-101, enters the absorption tower (C-101), operating at 1.2 bar, from the bottom, counter current to the lean solution (at approximately 35 wt% MEA concentration), which is fed to the top of the column at a T = 40 °C. A design specification is set that adjusts the lean solution flow rate so that 80% of the CO_2 from the FG is captured. It should be mentioned that, owing to the large FG flow rate produced by the power plant, the simulation refers to 1/10 of the total flow rate, in order to have acceptable tower diameters (less than5 m). Accordingly, all the equipment has to be reproduced 10 times to process the entire FG. The rich solution from the bottom of the absorber is then sent, after preheating with the regenerated lean solution in E-103, to the top of the stripping column C-102, which is operated at a pressure of 2 bar. The rich solution is regenerated by means of a reboiler (T = 122 °C), and CO_2 is recovered from the top, after cooling to 35 °C in the condenser E-104. The regenerated lean solution, after mixing with the make-up stream, is recycled back to the absorber. The absorption and stripping columns were modelled according to a rigorous rate-based simulation. The main features of the two packed columns are reported in Table 3.

The process flowsheet of the carbon capture process with HPC developed in Aspen Plus™ is shown in Fig. 2. It is based on the process scheme proposed by Giammarco-Vetrocoke Engineering Srl, an Italian company specialized in CO_2 removal from gas mixtures [55].

In this configuration, the HPC solution is regenerated according to a dual pressure regeneration (DPR) scheme, which utilizes two strippers in parallel: a high-pressure (HP) stripper (C-102), and a low-pressure (LP) one (C-103). Since the large flue gases flow rate would result in columns with unfeasible diameters, the simulation refers to 1/4 of the total amount, *i.e.* the total number of columns and all the equipment have to be multiplied by 4 to process the entire gas flow rate produced by the

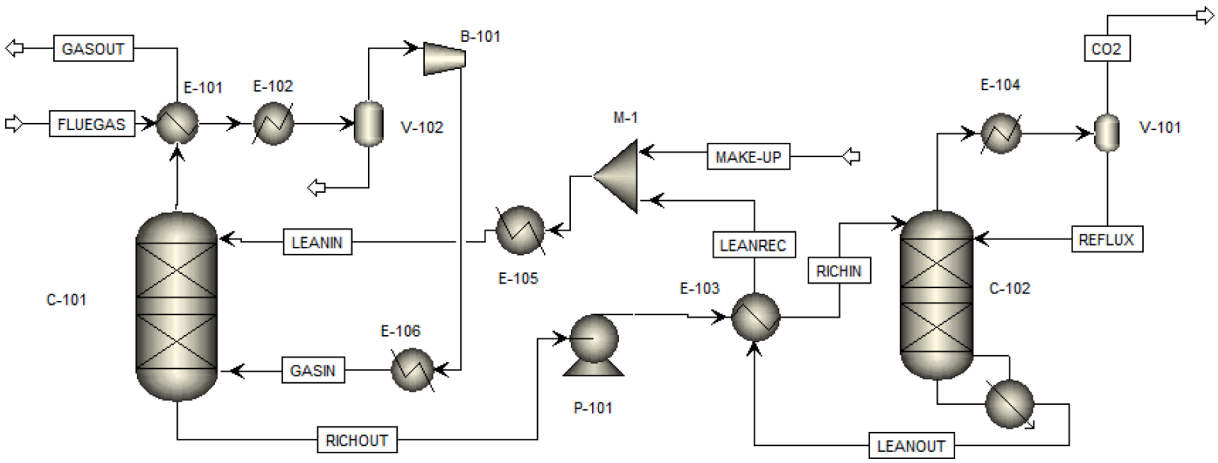

Fig. 1. MEA carbon capture process flowsheet within Aspen Plus™.

Table 3
Size and characteristics of the absorption and stripping columns of the MEA and HPC process.

MEA	Absorber C-101	Stripper C-102		
Packing type	Sulzer Mellapak 64X	Sulzer Mellapak 64X		
Column height (m)	31.5	34		
Column diameter (m)	4.5	2.2		
HPC	**Absorber C-101**	**HP stripper C-102**	**LP stripper C-103[a]**	
Packing type	Sulzer Mellapak 64X	Sulzer Mellapak 64X	Sulzer Mellapak 64X	
Column height (m)	20	20	20	3
Column diameter (m)	4.5	2.7	1.8	2

[a] This unit has two packing sections.

power plant considered here.

The FG from the stack (P = 1 bar, T = 143 °C) is cooled first in the gas/gas heat exchanger E-106 by the clean gas from the top of the absorber, and then to a T = 35 °C in E-104 by using CW. The cold gas is fed to a two-stage compressor K-101, which increases its pressure to the final value of 8 bar. About 50% of the compression power is recovered exploiting pressure reduction of the clean gas stream from the absorber in a turboexpander (K-102), coupled to the compressor. The compressed FG, before entering the absorption tower, is cooled down to a final T = 65 °C, first in the heat exchanger E-105 with part of the rich-solution stream which is preheated before entering the HP stripper, and then in the air cooler EA-103. The FG is hence treated in the counter current absorber with the lean solution (approximately 30 wt% of K_2CO_3), fed from the top at 65 °C. The column is sized in order to capture 80% of the CO_2 from the FG, by acting on the split ratio of S-2, which regulates the amount of lean solution to be recycled/purged. The main features of the packed absorption tower are summarized in Table 3.

The rich solution from the bottom of the absorber is regenerated according to the DPR system: 60% of the rich solution, after pre-heating in E-102 and E-105, is fed to the top of the HP stripper, operating at 2.1 bar. The regenerated lean solution from the bottom of this stripper, at about 130 °C, is laminated to the operating pressure of the LP stripper (1.2 bar), where it is cooled to about 110 °C. This process produces flashing vapour which is utilized for the regeneration of the remaining 40% of the rich solution stream, fed to the top of C-103. In this way, the amount of LP steam supplied to the reboiler of the HP stripper is the one

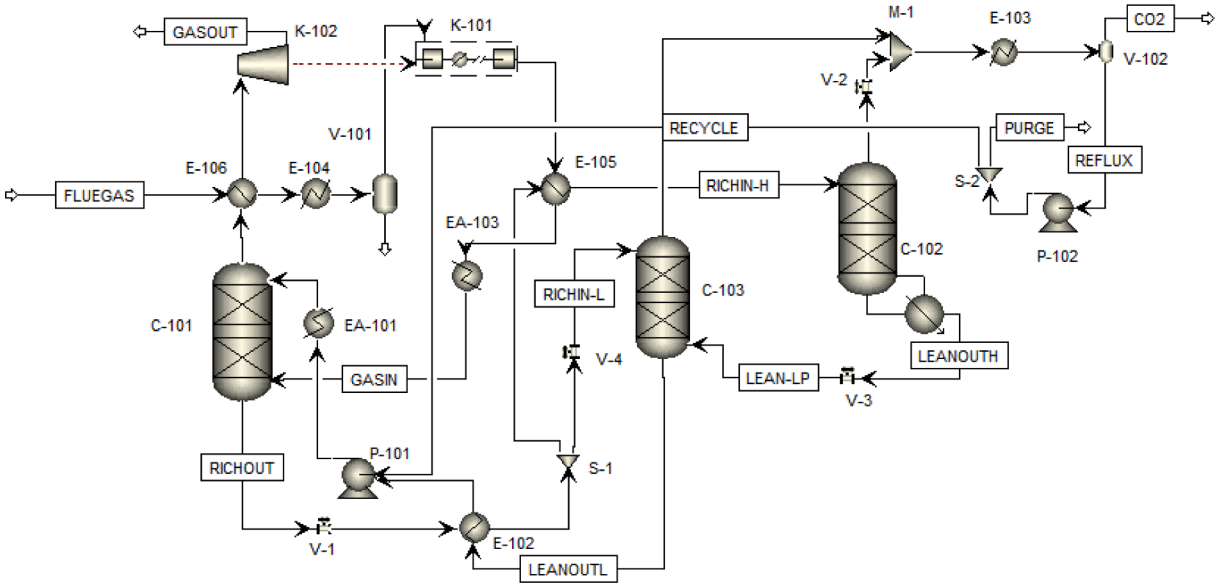

Fig. 2. HPC carbon capture process flowsheet within Aspen Plus.

strictly required for the regeneration of 60% of the rich solution, while the remaining 40% is regenerated only by recovered steam, thus achieving significant energy savings. The characteristics of the HP and LP strippers are also reported in Table 3.

The lean solution from the LP stripper is cooled down to 65 °C, first in E-102 and then, after mixing with the condensate separated in V-102, and being brought to the required pressure of 8 bar by P-101, using the air-cooler EA-101. The CO_2-water gas streams from the top of the two strippers are mixed, and then cooled down to T = 45 °C in E-103. The final vapour stream separated in V-102 is available at 1 bar and at 99.7 mol% CO_2 purity (on a dry basis), while the condensate is recycled by the pump P-102 to the suction of P-101 to maintain the required water balance of the system.

By using the Aspen Energy Analyzer™ (v.11) tool, it was verified that the process configurations depicted in Figs. 1 and 2 maximize the heat integration of the processes, hence minimizing the energy duty to be supplied by external utilities. It should be specified that validation of the simulation results was performed on the base of personal communications about the HPC process, by comparing the simulation results with data communicated directly by Giammarco-Vetrocoke Engineering Srl [55]. As for the MEA process, which is a well consolidated process for CO_2 capture from flue-gases, the model used in this work has been widely validated [56] and the results of our simulations are consistent with those reported in the literature.

After being recovered from the stripping units, CO_2 needs to be compressed and transported to the storage site. According to the Aspen Plus™ process flowsheet shown in Fig. 3, the CO_2 stream obtained from the capture process (either MEA or HPC) is compressed up to a pressure of 150 bar [44] by means of a 6-stage centrifugal compressor, with inter-stage cooling at 35 °C. The water condensed after each cooling stage is removed prior to injection to the following compression stage. In the last stage, CO_2 is cooled down to a final temperature of 15 °C. In these conditions, CO_2 is in the liquid state. For each stage, a polytropic efficiency of 86% and a mechanical efficiency of 98% are assumed [44]. Given the mass flow of CO_2 to be transported (about 45 kg/s at 99.5% mole purity), a pipeline diameter of 0.25 m was set. Considering pipelines to be located underground, transport is assumed to be isothermal at 15 °C, meaning that there is a sufficient heat exchange with the surrounding soil.

Actually, the fluid transport occurs in conditions intermediate between isothermal and adiabatic ones. However, Zhang et al. [53] demonstrated that there is not a substantial difference between these two conditions when CO_2 is in liquid state. The length of the pipeline is calculated in order to have a total pressure drop equal to 50 bar, corresponding to CO_2 outlet pressure of 100 bar, which is the value considered suitable for the following injection into the storage site. Pressure drops are calculated using the Darcy model for incompressible fluids. The resulting length is equal to 190 km [57]. If the distance between the capture site and the storage location is larger, one or more booster pumps are needed to re-pressurize the liquid CO_2 stream up to 150 bar, thus sustaining additional 190 km.

2.3. Energy Return On Energy Invested

Several methods and indices can be used to assess the efficiency of electrical energy production. A recent review [58] described different indicators and the mutual relationships among them, concluding that the best method for comparing different energy production industries is Net Energy Analysis (NEA). The goal of NEA is to calculate whether the energy produced by any production process is greater than the energy required to build, operate and maintain the infrastructure [59], taking also into account the energy required to extract the energy resources and convert them [60].

NEA is used for estimating the Energy Return Ratio (ERR) of an energy source, which takes into account the amount of energy consumed in the production process and compares it with the amount of energy available: different ERR methods and standards have been proposed, such as the Net Energy Ratio (NER), Net Energy Gain (NEG), and EROEI. More details about these three indicators are reported in the Supplementary Material.

A summary of the indicators and their relationships is reported in Fig. 4.

The objective of this paper is to compare, for a given electrical energy gas-fired production plant, the EROEI of the energy production with and without a carbon capture and storage process coupled to the production plant.

The definition of EROEI is:

$$EROEI = E_{out}/E_{in} \quad (1)$$

where E_{out} is the available electrical energy that the process provides and E_{in} is defined as:

$$E_{in} = E_{cap} + E_{o\&m} + E_f \quad (2)$$

In Eq. (2) E_{in} is the total energy that is provided and consumed during the production and operations periods of the plant and is made up of three contributions: E_{cap} is the capital energy embodied in the materials and used for construction and decommissioning of the plant; $E_{o\&m}$ is the energy needed for operating and maintaining the power plant; E_f is the energy needed for procuring and distributing the fuels, which includes also the energy used for extracting, refining and transporting the fuels from the production well to the power plant. All terms are expressed in GWh for consistency: the EROEI is thus dimensionless.

The detailed definition and functional dependency of the different contributions will be considered separately for the process without and with CCS.

Energy Return On Energy Invested for the power plant without carbon capture and storage

For electrical energy production from natural gas, the available electrical energy E_{out} is defined as:

$$E_{out} = P \bullet cf \bullet L \quad (3)$$

where P is the net power output, obtained by subtracting the auxiliary

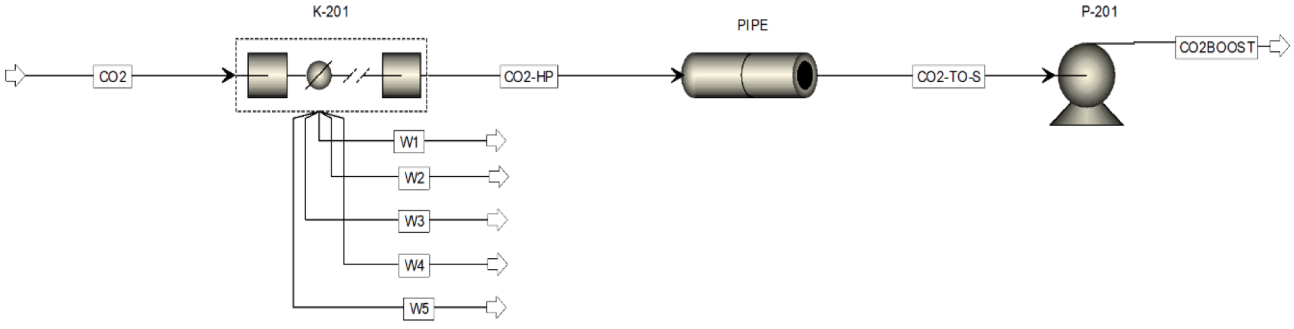

Fig. 3. CO_2 transport process flowsheet within Aspen Plus™.

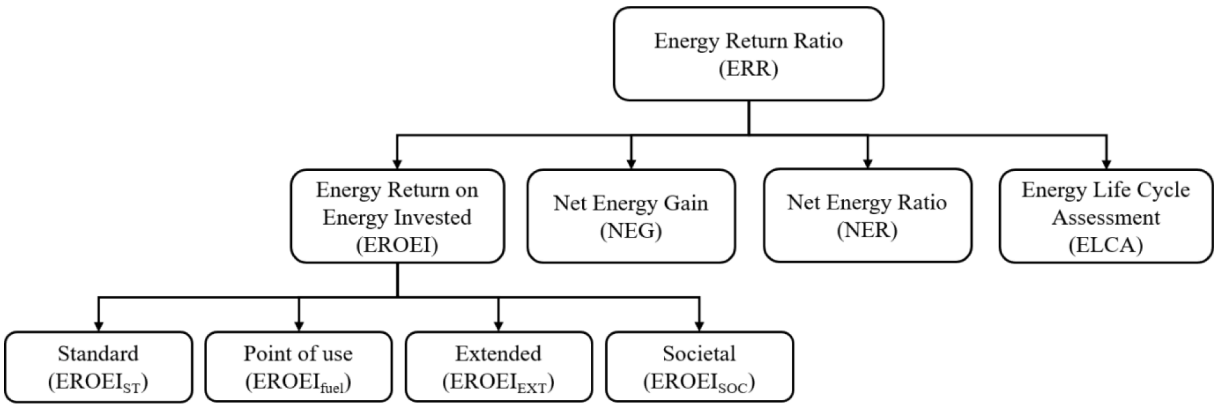

Fig. 4. Different indices for evaluating the energy return ratio ERR [58].

power requirements from the total installed capacity, cf is the capacity factor for the energy production plant (ranging from 0.40 to 0.85) and L is the plant life time (in years). The capacity factor for a NGCC power plant is the ratio of an actual electrical energy output over a given period of time to the maximum possible electrical energy output over that period.

The thermal energy involved is defined as the electrical energy production E_{out} divided by the global efficiency of the energy production plant (η):

$$E_{th} = E_{out}/\eta \tag{4}$$

Since the total efficiency is less than 1 (plant data ranges from 0.5 to 0.6), E_{th} is larger than E_{out} and represents the total energy provided to the process in the form of fuel.

The capital energy embodied in the materials and used for construction and decommissioning of the plant E_{cap} is defined as follows:

$$E_{cap} = P \bullet \varepsilon \tag{5}$$

where ε [kWh$_{el}$/kW] is the embodied capital energy per installed unit of power produced and is calculated according to:

$$\varepsilon = \frac{TPC}{P \bullet \varepsilon_c} \tag{6}$$

In Eq. (6) TPC is the total plant cost and ε_c is the proportionality coefficient between the costs of energy and capital costs. In this work ε_c is considered constant and is evaluated from real plant data [20].

The energy needed for operating and maintaining the power plant $E_{o\&m}$ is defined as:

$$E_{o\&m} = P \bullet \varepsilon \bullet L \bullet s_{o\&m} \tag{7}$$

where $s_{o\&m}$ is the share of the investment costs dedicated to operation and maintenance (ranging from 4% to 20% according to the different technology).

The energy needed for procuring and distributing the fuels, E_f, is defined as:

$$\frac{E_f = P \bullet cf \bullet L}{\eta \bullet EROEI_{fuel}} \tag{8}$$

In Eq. (8) only the term EROEI$_{fuel}$ refers to the energy used to extract, store, refine and transport the fuel [19] (Fig. 5), while the other terms

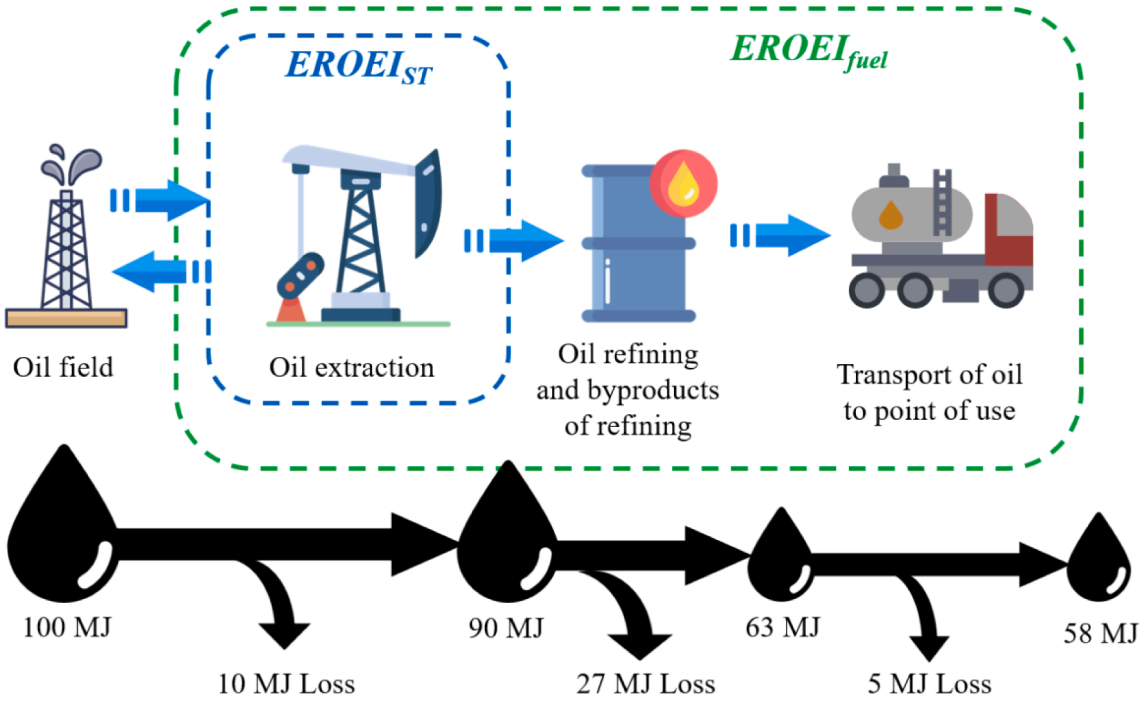

Fig. 5. System boundaries for the estimation of EROEI$_{fuel}$ [44].

are directly related to the plant dimensions and operations. Literature values of $EROEI_{fuel}$ from different recent sources are reported in Table 4. They take into account all the boundaries of various types of EROEI analyses and the energy losses associated with the processing of fuel as it is transformed from "fuel at the wellhead" to consumer-ready fuels.

According to [15], the net energy is likely to move from an abundant to a scarce resource if effective measures are taken to remain within a given carbon budget. In this context, the carbon budget is defined as the amount of CO_2 emissions permitted over a period of time to remain within a certain temperature threshold, namely 2 (or better 1.5) °C. With this aim, another indicator has been introduced [15], namely the Energy Return on Carbon (EROC): it allows a comparison of the performance of different energy sources under the constraint of climate change targets. The EROC is calculated as:

$$EROC = \left[\frac{(1 - 1/EROEI)}{(C_{ef})}\right] \quad (9)$$

In this work, we considered the Carbon Emission Factor (C_{ef}), expressed in $kgCO_2/GJ$, as the weighted average of the CO_2 emitted from electricity produced by natural gas. The C_{ef} is the result of the ratio between the CO_2 equivalent emission data divided by the gross electricity generation based on natural gas.

The EROC index takes into account both the net energy potential of a fossil fuel and its carbon emissions to produce an evaluation of the fuel's overall utility under climate change policy and is a powerful indicator of how efficiently the carbon budget is used. The CCS carbon emission factors needed in the calculations are taken from [15] and are based on capturing 85% of CO_2 emissions, according to the Intergovernmental Panel on Climate Change (IPCC) special report on CCS [61].

To summarize, the independent and the calculated variables for EROEI and EROC calculations are reported in Table S3 of the Supplementary Material, along with the units and indications of how they are estimated or calculated. Data for the estimation of the EROEI and EROC for the process without CCS are taken from the literature.

Energy Return On Energy Invested for the power plant with carbon capture and storage

The calculation of the EROEI when a CCS plant is added to the electrical energy production plant is performed according to the definition of the EROEI in Eq. (1) but with different values of the terms in Eq. (2).

When a CCS plant is considered for treating the emission of the natural gas electricity production plant, both E_{out} and E_{in} need to be modified to account for the energy consumed in the CCS process. E_{out} is reduced due to two effects: (i) the higher consumption of energy for auxiliary power, due to the electrical energy used for pumping and auxiliary work in the CCS plant and (ii) the thermal energy directly used in the reboiler of the stripping column. Information on both of these comes from the process simulation of the CCS plant. E_{out} and E_{th} are calculated according to Eq. (3) and (4).

E_{in} and its components E_{cap}, $E_{o\&m}$ and E_f are calculated according to Eq. (5), (7) and (8) defined above, but the values of the independent variables are now estimated according to the results obtained from the simulation of the CCS processes. In particular, TPC and $s_{o\&m}$ are evaluated by means of Capcost™ software based on the results from the process simulation (see Table 7 in the Results and Discussion section).

Levelized cost of energy

The LCOE, which is a measure of the electricity generation cost, was used in order to compare different power technologies. The LCOE is calculated as follows [62]:

$$\frac{LCOE = OC \bullet P \bullet CRF \bullet FO\&MC}{8760 \bullet cf + VO\&MC} \quad (10)$$

where OC [€/kW] is the overnight cost (cost per unit power produced), P [kW] is the net power output of the plant, CRF [-] the capital recovery factor, cf [-] the capacity factor, while FO&MC [€/kW/year] and VO&MC [€/kWh] are the fixed and the variable operation costs respectively. The overnight cost is calculated as the ratio between the total plant cost (TPC) relative to the CCS plant only and the net power output P (see Table 7 in the Results and Discussion section).

The capital recovery factor is:

$$CRF = \frac{i \bullet (i+1)^L}{(i+1)^L - 1} \quad (11)$$

where i [%] is the interest rate and L [years] is the plant life time.

When comparing LCOEs of different technologies whose yield depends on weather conditions (*i.e.,* solar radiation and wind), Germany is a good benchmark in Europe. In fact, the yield of a photovoltaic plant installed in Germany represents well the potential of this technology as this country has an average level of solar irradiation. With reference to Table 5, the German LCOE for photovoltaics and wind power is today not only competitive but in many cases smaller than the one for

Table 4
Literature values of $EROEI_{fuel}$ for different resources.

Resource	$EROEI_{fuel}$		
	Rana et al. 2020 [58]	King et al. 2018 [15]	Hall et al. 2014 [19]
Wind	16.7 – 17.7	5 – 18	18
Solar photovoltaic	5 – 34	4 – 25	6 – 12
Hydro		59 – 84	>100
Nuclear		14	5 – 15
Coal		46	27 – 80
Oil		19	11 – 65
Natural gas		19	20 – 67
Shale oil		7	
Tar sands		4	11

Table 5
LCOEs expressed in €/MWh for different technologies (without CCS); min–max values are reported in column 2.

Technology	LCOE (min–max) Today in Germany [41,63]	LCOE New installations: 2025 worldwide [41,63]
Photovoltaics	[30 –77]	29
Wind power	[40 – 82]	36 onshore, 109 offshore
Biogas	[100 – 115]	84
NGCC	[78 – 100]	34
Coal-fired power plants	[46 – 99]	68
Nuclear	NA	67

Table 6
Breakdown of energy duties for the MEA and HPC processes. kW_e indicates electrical energy duties, kW_{th} thermal energy duties, while u.o.m. stands for units of measure

MEA			HPC		
Process unit	Value	u.o.m	Process unit	Value	u.o.m
Blower (B-101)	20,945	kW_e	FG compressor (K-101 + K-102)	93,798	kW_e
Pump (P-101)	373	kW_e	Pumps (P-101 + P-102)	1,441	kW_e
CO2 compressor (K-201)	12,785	kW_e	CO2 compressor (K-201)	15,931	kW_e
Booster pump (P-201)	267	kW_e	Booster pump (P-201)	268	kW_e
Total auxiliaries	**34,370**	**kW_e**	**Total auxiliaries**	**111,438**	**kW_e**
Reboiler duty (C-102)	248,445	kW_{th}	Reboiler duty (C-102)	129,241	kW_{th}
	89,440	kW_e		46,527	kW_e
Total (auxiliaries + reboiler)	**123,810**	**kW_e**	**Total (auxiliaries + reboiler)**	**157,965**	**kW_e**

Table 7
Summary of data retrieved from process simulation for the estimation of EROEI, LCOE and LCA (cf = capacity factor of the NGCC power plant).

		MEA	HPC	EROEI	LCOE	LCA
Installed capacity (P_{inst})	**kW_e**	564,700	564,700	x	x	x
Energy for auxiliary[a]	**%**	7.8	21.4	x		x
Thermal energy[b]	**%**	84.2	91.75	x		x
Net power output (P)	**kW_e**	431,431	397,266	x	x	x
Total plant cost (TPC)	€	246,610,100 (CCS only)	522,848,300 (CCS only)		x	
		576,394,900 (CCS + NGCC)	852,663,100 (CCS + NGCC)	x		
Share of investment costs due to operation and maintenance ($s_{o\&m}$)	**%**	12.4	13.15	x		
Fixed operation and maintenance costs (FO&MC)	**€/kW/year**	67.28	143.18		x	
Variable operation and maintenance costs (VO&MC), cf = 0.4	**€/kWh**	0.020	0.030		x	
Variable operation and maintenance costs (VO&MC) cf = 0.85	**€/kWh**	0.009	0.014		x	
Total amount of solvent[c]	**kg**	53,317,213	9,691,908			x

[a] expressed as % of the installed capacity
[b] it indicates the % of power energy produced by the NGCC plant after subtraction of the LP steam required by solvent regeneration with respect to the installed capacity.
[c] calculated for cf = 0.4 and lifetime of 30 years.

conventional sources [63]. Moreover, according to the U.S. Energy Information Administration (EIA) forecasts, this situation is predicted to continue worldwide in the future [41].

The LCOE for NGCC power plants with CCS are calculated starting from the German costs listed in Table 5 as follows:

$$LCOE = [78 - 100] + LCOE_{CCS} \quad (12)$$

where $LCOE_{CCS}$ [€/MWh] is the generation cost due to the carbon capture and storage. This has been calculated from Eq. (10) using the values listed in Table 7 in the Results and Discussion section, obtained by process simulations. Specifically, the TPC is in this case the one referring to the CCS plant only. The interest rate has been set to 7.3% as in [1].

2.4. Life Cycle Assessment

Following the International Standard Organization (ISO) 14,040 [64] and ISO 14,044 guidelines [65], LCA enables practitioners to predict the potential emissions to environmental compartments (*i.e.*, soil, water and atmosphere) coming from the system under investigation. The LCA procedure employs material and energy balances over the entire life cycle of the product system, taking into consideration the extraction of raw materials, manufacturing, use phase, end-of-life and the transportation between life cycle stages [66]. The results of life cycle assessments are depicted by means of several impact categories, which are able to represent the entire range of ecological burdens associated with the product system, avoiding shifting the impact among environmental compartments. The LCA procedure involves the implementation of four main phases: goal and scope; Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation. Every step has been discussed in depth in a series of publications dealing with the characteristics of the goal and scope and life cycle inventory [67] and impact assessment and interpretation practices [68].

The aim of this LCA investigation is to evaluate the environmental impacts related to the introduction of the most promising CCS configurations in series to a gas-fired combined cycle power plant. Although for this application there is no evidence of an industrial-scale process yet, the most well-established technologies for CCS involve MEA and potassium carbonate as suitable solvents. Hence, these two technologies have been included in this study. In addition, a comparison among CCS power plants, an up-to-date photovoltaic plant and a wind turbine installation is performed, aimed at identifying the best option in terms of environmental footprint. The functional unit is defined as "1 kWh of high-voltage electricity generated through an available technology in Europe". Germany has been selected as a representative country for Europe due to its average solar irradiation within the continent. The system boundary includes the extraction of raw materials and fossil fuels, the manufacturing of power and carbon capture plants and operating activities, including transport and storage of CO_2, representing a cradle-to-gate approach. The calculations have been performed using openLCA™ 1.10.1 and the background data have been mainly retrieved within ecoinvent v3.7 [69]. As previously mentioned, process simulation provided the material and energy balances of the CCS plant, which are not available within well-established databases. Advanced process modelling for life cycle inventory generation is an acknowledged technique, as it has been used in several applications, such as the production of methanol [70], acrylic acid [71], active pharmaceutical ingredients [72], organic compounds [73] or the separation of phenol from aqueous streams [74].

2.4.1. Life cycle inventory

The inventory of ecoinvent processes describing the electricity production from natural gas in a 400 MW_e NGCC has been selected as a reference process for electricity generation from natural gas [75]. Since the carbon capture plants have been dimensioned on the emissions generated from a 550 MWe power plant, the materials employed for gas power plant facilities have been scaled accordingly. In addition, the natural gas consumption of 0.2017 m^3/kWh, which has been reported in [44] for an equivalent size plant, has been chosen as a reference value and the related emissions and water usage have been scaled proportionally.

The carbon capture inventories are based both on process simulation and on the ecoinvent database. The former provided the amounts of solvents, water and the main equipment material, while the latter supplied raw materials data as well as the materials mix for ancillary equipment and infrastructures estimated on a distillation unit that was assumed similar to the one needed for carbon capture operation. Carbon capture plants have been added to the traditional power plant, together with 190 km of pipeline for the subsequent average transport onshore of captured CO_2 towards a geological formation for final storage. The energy required for the overall CCS operation has been supplied by the power plant itself through an increment of the natural gas inlet flow rate, mainly for solvent regeneration and electricity production for flue gas compression. The emissions related to the MEA-based capture plant have been retrieved from Veltman [23], whose results are in agreement with the ecoinvent data for an NGCC power plant. Therefore, the provided detailed emissions related to the MEA carbon capture unit were implemented within the ecoinvent database emissions, including MEA, ammonia (NH_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), formaldehyde and acetaldehyde, whose amounts have been calculated following the emission ratios identified in Veltman's work. Since there is no evidence of specific emissions related to the degradation of potassium carbonate from an HPC-based capture plant [34], no further emission was added to this capture operation.

The photovoltaic installation inventory (PV) is based on a 570 kWp photovoltaic plant available within the ecoinvent database. Since the functional unit is represented by a single kWh produced, the different sizes of the electricity generation power plants do not lead to inconsistencies among the different options. Furthermore, because photovoltaic is a modular technology, it is possible to build up electricity generation plants of any sizes, which can still be represented by the process system used in this study. However, in order to provide updated information on the actual materials employed, some changes have been implemented. Firstly, a single technology, *i.e.*, polycrystalline-Si, has been employed, as it represents the majority of the market share. Starting from the wafer production, the actual thickness is 180 μm, reducing the material requirements to 75% of the ecoinvent inventory, which refers to a 240 μm thickness. Moreover, the ecoinvent database reports a cell efficiency of 13.5%, while an up-to-date value of 18% appears more reasonable. The energy produced during the total lifetime of the plant (30 years) has been calculated using the solar radiation for Frankfurt, Germany, which has been taken as an average for the whole country.

Wind electricity production (W) has been modelled using the life cycle inventory of an onshore grid-connected wind power plant in Germany with a capacity greater than 3 MWe. It includes operation and maintenance expenditures as well as infrastructure inputs in 2012. Further information can be retrieved within the ecoinvent documentation [75].

3. Results and discussion

Process simulations allowed to obtain detailed material and energy balances for the two CCS configurations investigated, which are necessary for the subsequent evaluation of the EROEI, LCOE, and LCA indicators.

3.1. Process simulations

Table S4 in the Supplementary Material summarizes the detailed simulation results (flow rate, composition, temperature and pressure) of the most relevant streams for the MEA and HPC capture and transport processes, with reference to Figs. 1, 2, and 3. In both cases, according to the FG input reported in Table 2, the total flow rate of CO_2 in the inlet stream to the capture section is equal to 56.2 kg/s. The capture yield has been set to 80% of the inlet one. As a result, roughly 45 kg/s of CO_2 are recovered from the capture facility and delivered to the compression and transport unit, while about 11 kg/s are emitted from the stack. The CO_2 stream prior to the compression step is characterized by a higher purity (lower water content) in the MEA process, as a consequence of the higher pressure and lower temperature employed in the condensation stage. The higher pressure is also reflected in lower CO_2 compression work requirements (Table 6). Nonetheless, after the compression stage, the CO_2-HP stream is characterized by purities higher than 99.5% in both cases. A big advantage of HPC over MEA is that the solvent is not volatile, and is less prone to oxygen degradation, so that little to no make-up is required in this case.

Most interesting is to analyse and compare the overall energy balance of the two process routes, to understand the corresponding energy penalties. Table 6 summarizes the breakdown of the power and thermal energy duties of the MEA and HPC processes.

When strictly considering the reboiler duty for the regeneration of the lean solution, which is reportedly the major energy contribution to CCS by chemical absorption, HPC clearly outperforms the MEA process, with roughly half the heat requirements (129 MW_{th} vs. 248.5 MW_{th}, corresponding to 2.87 MJ_{th}/kg_{CO2} and 5.5 MJ_{th}/kg_{CO2}, respectively). This is achieved thanks to the dual pressure regeneration scheme that allows the saving of about 40% of regeneration duties by exploiting the pressure difference between the two strippers. This occurs since the HPC solvent is regenerated by means of a pressure swing, while MEA regeneration follows a temperature swing mechanism. The duty found from the simulations is in the higher range of the values reported for MEA absorption [76]. With respect to that, it should be considered that most of the works in the literature consider carbon capture from coal-based power plants, where the CO_2 content in the FG is in the range of 8–12 mol%, thereby increasing the driving force for absorption/regeneration and reducing the specific heat duty. In addition, while a number of process modifications (such as absorber intercooling or stripper overhead compression) have been investigated to reduce the reboiler duty [77], the additional equipment and related heat/power consumption mostly compensate for the improvement achieved.

In both cases, the heat needed for solvent regeneration is assumed to be taken from low pressure (LP) steam, withdrawn from the power plant cycle. Accordingly, the electrical energy output of the power plant will be reduced by a certain amount as a consequence of the lower flow rate delivered to the LP steam turbine. This is quantified by converting the reboiler heat duties (kW_{th}) into equivalent power (kW_e), assuming an efficiency of 36% [77]. As can be seen in Table 6, the reboiler duty of the stripping represents one of the major energy burdens of CCS (72% of the total duty for MEA, and 29.5% for HPC).

Despite the large savings achieved in terms of reboiler duty, the HPC process requires a substantial amount of energy for the FG compression up to the operating pressure of the absorber. Even though roughly 50% of the compression work can be recovered thanks to the coupled turbo-expander, the energy amounts to about twice the equivalent power needed for solvent regeneration. Alternatively, the stripper could be operated under vacuum, which would, however, result in significantly larger column diameters. The compression work has a large impact on the overall energy requirement of HPC-CCS (about 60% of the total duty), which is due also to the large FG flow rate (and low CO_2 content) to be treated. This has an impact on the overall energy efficiency of the process. Accordingly, from a purely energetic standpoint, HPC would appear to be greatly beneficial compared with MEA absorption when treating gaseous streams available at higher pressures, while for FG it does not appear advantageous.

The third significant contribution to the overall CCS energy cost is represented by CO_2 compression. The specific energy consumption is equal to 80 kWh_e/t_{CO2} (13 MW_e) and 98 kWh_e/t_{CO2} (16 MW_e) for MEA and HPC, respectively, which is in line with values reported in the literature [78]. The former is lower thanks to the higher regeneration pressure in the stripper. Overall, CO_2 transport is responsible for roughly 10% of the overall energy costs of CCS.

Ultimately, the EROEI, LCOE, and LCA will allow a better comparison of the two CCS process routes considering also economic and environmental aspects, and assessing the impact that CCS has on the overall energetic efficiency of an NGCC power plant. Moreover, they make it possible to compare this greenhouse gas (GHG) mitigation strategy with the adoption of renewable energy sources. The material and energy balances obtained from the process simulations were elaborated to derive the parameters required to perform the subsequent analyses and are summarized in Table 7.

3.2. Energy Return On Energy Invested

Equations defining the EROEI and EROC (Eq. (1) and (9)) were used together with the data in Table 8 to estimate the EROEI and EROC for the energy generation process without carbon capture and for the process with CCS using MEA or HPC. Table S3 in the Supplementary Materials summarizes the data used for the calculation, indicating if the data are taken from literature, from process simulation results or if they are fixed values or parameters.

The EROEI data for natural gas to be used for the $EROEI_{fuel}$ of NG are taken from Table 4 as a mean value from the different sources (value used for calculations = 44).

The final values of the EROEI and EROC for the processes of interest are reported in Table 9. The addition of CCS to the power plant has the

Table 8
Data used for EROEI estimation; $P_{inst} = 564{,}700\ kW_{el}$, $\varepsilon_c = 0.6560$, L = 30 years, $\eta = 0.60$, $EROEI_{fuel} = 44$.

Independent variable	Name	Unit	NGCC no CCS	NGCC + CCS MEA	NGCC + CCS HPC
Energy for auxiliary		%	1.7	7.8	21.4
Thermal energy for CCS		%	0	84.2	91.75
Total product cost	TPC	k€	329,784.8	576,394.9	852,663.1
Share of investment costs for operation and maintenance	$s_{o\&m}$	%	0.040	12.40	13.15
Carbon emission factor	C_{ef}	$kgCO_2/GJ$	56.1	5.6	5.6

direct effect of lowering substantially the EROEI value, because of the higher energy consumption for the capture and storage process. Both thermal and electrical energy are used in the process for the auxiliaries and for supplying heat for the separation process. The EROEI reduction is much more pronounced for the HPC process. In all cases, the EROEI is directly proportional to the capacity factor, as expected.

The EROC calculations for processes with and without CCS are in line with literature values [15]. Since the EROC takes into account both the net energy potential of a fossil fuel and its carbon emissions, it allows a comparison of the performance under the constraint of climate change targets. In this respect, it is not surprising that the EROC values for CCS are one order of magnitude larger than that of the pristine process.

3.3. Levelized Cost Of Energy

The LCOE calculation was performed choosing two pairs of plant life time and capacity factors according to global [41] and local data [62]. The results of the calculations are summarized in Table 10.

Compared with the LCOEs listed in Table 5, the results of Table 10 clearly show that the cost of electricity produced from natural gas with CCS is much higher than the costs from photovoltaics and wind power, particularly when the capacity factor is low. For instance, when the capacity factor is 0.40, the LCOE of NGCC with MEA is double that of photovoltaics, while that of NGCC with HPC is almost triple that of photovoltaics. The results for NGCC are better when the capacity factor is increased to 0.85, but they are still not competitive with respect to renewables. This is due to the cost of the process of carbon capture and storage that alone (*i.e.,* without considering the production of electricity) is very high and in the range of (24–100).

3.4. Life Cycle Impact Assessment

A comparison among NGCC, MEA-CCS, HPC-CCS, PV and W has been performed using the environmental categories employed by the Environmental Footprint (EF) v2.0 method, as implemented within openLCA™. This method deals with every environmental compartment through well-established impact categories groups: climate change (CC-T) covering biogenic, fossil, and land exploitation contributions; ecosystem quality, which includes freshwater and terrestrial acidification (EQ-FTA), freshwater ecotoxicity (EQ-FE), marine eutrophication (EQ-EM), eutrophication of freshwater (EQ-EF) and terrestrial eutrophication (EQ-ET); human health, which involves the evaluation of impacts related to carcinogenic (HH-CE) or non-carcinogenic effects (HH-NCE), ionizing radiation (HH-IR), ozone layer depletion (HH-OD), photochemical ozone creation (HH-PCOC), and respiratory effects (HH-RE); resources depletion concerning the impacts on available raw materials such as dissipated water (RD-W), fossil fuels (RD-F), land (RD-L) and minerals and metals (RD-M). The scores of each impact category are shown in Fig. 6, where a comparison among the considered technologies can be performed. For further details, see Table S5 of the Supplementary Materials.

Table 9
Calculated values of EROEI [-] and EROC [GJ / tCO_2] for the systems studied at two different values of cf.

Process	cf	EROEI	EROC
NGCC	0.40	17.60	16.81
	0.85	21.37	16.99
NGCC + CCS MEA	0.40	7.73	163.1
	0.85	12.36	167.1
NGCC + CCS HPC	0.40	5.21	163.1
	0.85	9.06	167.1

Table 10
LCOEs expressed in €/MWh for an NGCC power plant using the two considered CCS technologies as a function of the capacity factor for a plant life time L = 30 years.

cf	NGCC with MEA	Extra cost due to MEA	NGCC with HPC	Extra cost due to HPC
0.40	[131 – 153]	53	[178 – 200]	100
0.85	[102 – 124]	24	[126 – 148]	48

It can be seen that the results for several impact categories are mostly driven by natural gas utilization, in terms of extraction, refinement, transportation and combustion. Indeed, the highest impacts exhibited by HPC-based CCS on resource depletion of fossil fuels (RD-F) and human health (HH-OD and HH-PCOC) can be attributed to the highest energy consumption of these configurations. As a result from the process simulation, this is due to the energy required for the compression of the large flow rate of flue gas, which exceeds the energy necessary for the regeneration of MEA. Besides the previous impact categories, CC-T is also related to the combustion of natural gas, but in this case, thanks to the carbon capture process, NGCC is revealed as the worst choice. In relation to numerous impact categories (CC-T, EQ-FTA, EQ-EM, EQ-ET, HH-OD, HH-PCOC, RD-F), it is worth noticing how the impacts of photovoltaic and wind installations are very low in comparison with those of fossil fuel-based technologies. Since the development of CCS is driven by the need to mitigate greenhouse gases emission quantified by CC-T, it appears clear how renewable technologies, in this case photovoltaic or wind installations, perform better than CCS in this direction. However, attention must be paid to avoiding burden shifting among the environmental compartments. For instance, eutrophication-related impact categories exhibited greater values for fossil-based technology when dealing with categories related to nitrogen emissions (EQ-EM, EQ-ET), while higher scores have been obtained by renewables for phosphorus-related categories (EQ-EF). This is mainly due to the extraction and refinement of metals (mostly copper and aluminium) employed for the construction of the power plants. Furthermore, both water and minerals resource depletion (RD-W, RD-M) are higher for PV and W due to the materials and water involved in the panel and turbine construction. In addition, the extraction of raw materials generates large impacts for the aquatic environment (EQ-FE), for human health (HH-CE, HH-IR, HH-NCE, HH-RE) and for land use (RD-L), worsening the performances of renewable sources even further.

3.4.1. Sensitivity analyses

Throughout this investigation, several assumptions have been made in order to guarantee consistency with the primary data obtained for electricity generation [44]. However, since the results are affected by these hypotheses, a number of sensitivity analyses have been performed with the aim of discussing different scenarios, particularly the effects of ecoinvent data modifications.

The first sensitivity analysis focuses on the effects of a different capacity factor for natural gas with and without CCS. Since the functional

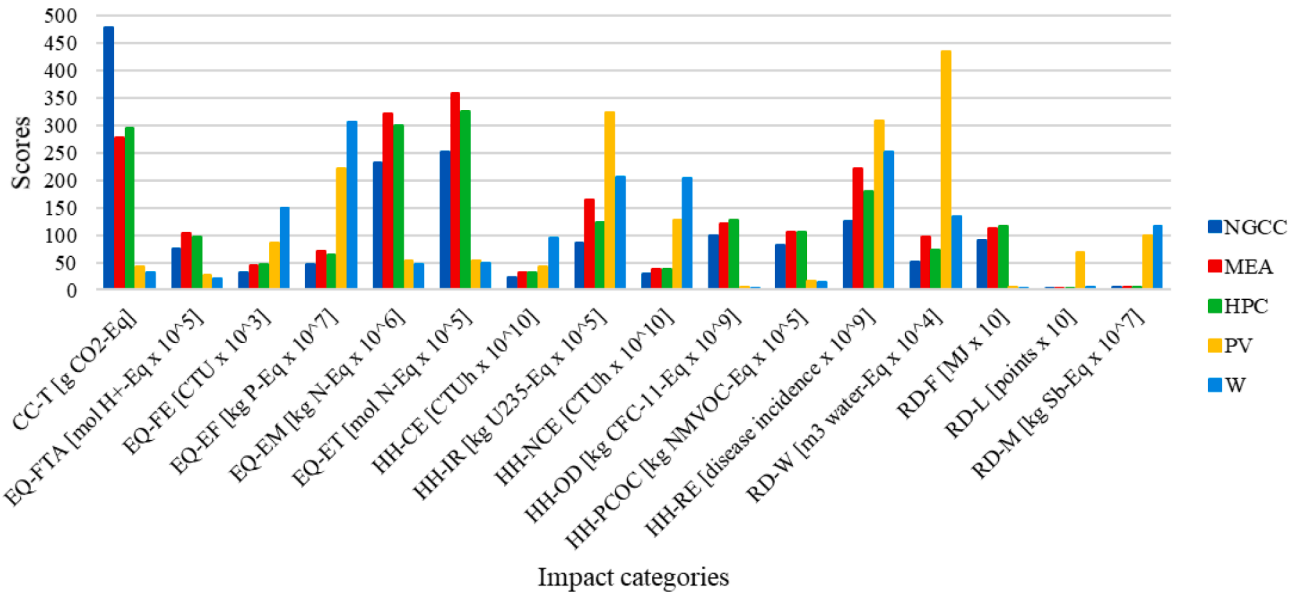

Fig. 6. Impact categories scores for each power generation technology considered in this study. NGCC: Natural Gas Combined Cycle, MEA: Monoethanolamine-based CCS, HPC: Hot Potassium Carbonate-based CCS, PV: photovoltaics, W: wind.

unit has been set to 1 kWh, operation activities do not affect the final scores due to normalization. Therefore, this analysis focused mainly on the different impacts of pieces of equipment and infrastructures for NGCC and CCS. An updated report on energy production in Germany was followed, which reports a capacity factor of 0.40 for NGCC power plant [41], while a standard value often used in the literature is 0.85 [20]. The lifetime of the plant has been set to 30 years for both alternatives. The results, which are shown in Table S6 of the Supplementary Material, exhibit a general decrease in the environmental footprint for the highest capacity factor, thanks to the greater amount of energy produced throughout the entire lifetime of the infrastructure and equipment. However, more than doubling the capacity factor did not provide substantial decrements among the various impact indicators. The most affected environmental categories averaged among the three NGCC configurations were the ones related to the depletion of minerals and metals (RD-M, −28%), to human health in terms of carcinogenic effects (HH-CE, −14.4%), to freshwater ecotoxicity (EQ-FE, −12.6%), land consumption (RD-L, −12.5%) and freshwater eutrophication (EQ-EF, −10.7%). As expected, these indicators quantify the impacts caused by the emissions deriving from the extraction of the raw materials involved in the construction of equipment and the erection of infrastructures. The sensitivity analysis on the utilization of the power plant highlighted how a variation in the capacity factor has a negligible influence on the mutual relationship among the power generation alternatives. In fact, the relative performances among the available options are essentially constant, the renewable-based technologies being the most burdensome for the impact categories affected by raw materials extraction.

A second sensitivity analysis takes into consideration the specific natural gas consumption for the production of 1 kWh of electricity. Ecoinvent reports a natural gas consumption of 0.1637 m^3NG/kWh, while reference [44] declares 0.2017 m^3NG/kWh. This is mainly due to variability in the round-trip efficiency of the NGCC power plant. Since the natural gas consumption affects every impact category, each indicator belonging to natural gas power generation is subjected to an average decrease of about −18%, as reported in Table S7 of the Supplementary Material, when the natural gas consumption is decreased to the lower value. Notwithstanding the absolute scores of impact categories decreasing, the relative position among the NG-based power generation alternatives does not change substantially, and neither do their relative performances in comparison with the renewable sources.

The last sensitivity analysis aims to assess the effect of different emission of CO_2 from 1 m^3 of natural gas. This variability comes from different compositions of natural gas and/or different transport conditions. Ecoinvent reports an emission of 2.083 $kgCO_2/m^3NG$, while a specific report [44] exhibits emissions for 1.813 $kgCO_2/m^3NG$, influencing several impact indicators, as reported in Table S8 of the Supplementary Material. To confirm the expectations, the most affected environmental category is revealed to be CC-T, since increasing the specific emission of carbon dioxide to the ecoinvent value generates an average growth of 8.8% among the NG-based power generation technologies, with a maximum of 11.4% increment for the configuration without CCS. As in previous analyses, the relative performances between fossil and renewable-based technologies are not significantly altered by an increase of 15% of CO_2 specific emission.

The sensitivity analyses focused on natural gas power plant operating conditions, ranging over the capacity factor (0.4–0.85), natural gas consumption (0.1637–0.2017 m^3NG/kWh) and CO_2 specific emission (1.813–2.083 $kgCO_2/m^3NG$). Although the impact categories values exhibited variations due to modifications of the parameters, the critical analysis previously discussed on the advantages and drawbacks of each technology is confirmed, as the relative performances among the various alternatives were not remarkably influenced by the sensitivity analyses.

4. Conclusions

In this work, a comprehensive analysis of the real industrial size power production from natural gas equipped with a carbon capture and storage system was carried out, linking data obtained by means of detailed process simulation of two CCS routes to the calculation of the EROEI, LCOE and LCA indicators. Specifically, the values of these indicators were compared for a power plant with or without CCS, and for the technologies which are the drivers of the energy transition: photovoltaics and wind power.

Process simulations show that, in general, CCS applied to NGCC power plants is more energy-intensive compared to the data reported for coal-based plants, due to the high FG flow rate with lower CO_2 content. HPC absorption outperforms MEA in terms of reboiler duty for solvent regeneration, but is characterized by significantly high FG compression loads, due to the higher operating pressure. The CCS processes reported in this work reveal that a power of 123.810 kW is used to supply energy to the auxiliaries and the reboiler of the MEA CCS-based power plant,

while 157.965 kW are needed in the case of HPC CCS, mainly due to the high FG compression loads. The energy used to power the auxiliaries is 7.8% of the nominal power for MEA and 21.4% for HPC. This energy consumption reduces substantially the net power output of the power plant with CCS. The results from PS were transferred to the LCOE, EROEI, EROC and LCA estimation methods.

The addition of CCS to the power plant has the direct effect of lowering substantially the EROEI: for a capacity factor of 0.4 the reduction is 56% for MEA and 71% for HPC. This is due to the higher energy consumption for the capture and storage process coming from the thermal and electrical energy used for auxiliaries and for supplying heat for the solvent regeneration process. The EROEI reduction is much more pronounced for the HPC process. In all cases, the EROEI is directly proportional to the capacity factor, as expected. In addition, the EROC values for CCS are one order of magnitude larger (around 163.1–167.1 with CCS compared to 16.81–16.99 without CCS) than that of the pristine process.

As far as the LCOE is concerned, the results clearly show how the cost of electricity produced by natural gas with CCS is notably higher than the costs from photovoltaics and wind power, particularly when the capacity factor is low. The LCOE for a capacity factor of 0.4 ranges between 131 and 200 €/MWh.

The advantages and drawbacks of each electricity generation technology emerge thanks to life cycle assessment. Fossil-based power plants exhibit higher impacts in climate-related categories (climate change, ozone depletion, photochemical ozone creation), eutrophication (both terrestrial and marine) and acidification, primarily due to the combustion of natural gas. Conversely, photovoltaics and wind power generation are found to be detrimental towards human health and freshwater (in terms of ecotoxicity and freshwater eutrophication) as the extraction of the minerals required for their construction has a significant environmental footprint.

In summary, this paper introduces a new paradigm in process design by coupling process simulation with environmental/economic indicators such as the EROEI, LCOE and LCA. The procedure is applied to CCS coupled with an NGCC power plant, selected for the great relevance of the role of CCS at the current time. The proposed method and procedure are not limited to the example reported and can be used for similar industrial processes such as hydrogen production, solvent extraction and other separation technologies, polymer recycling, and so on.

The results reported show that the coupling of CCS with NGCC power plants as a key technology enabling energy transition may not be so convenient overall. In particular, if the aim of CCS is purely to reduce GHG emissions, renewable power sources appear much more convenient. However, further analysis should be carried out on a case-by-case basis, since large-scale CCS plants are not yet operating in the power sector. In any case, the EROEI, LCOE and LCA indicators should always be accounted for, if a fair analysis is to be carried out.

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CRediT authorship contribution statement

Elena Barbera: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Andrea Mio:** Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Alessandro Massi Pavan:** Data curation, Investigation, Methodology, Validation, Writing – original draft. **Alberto Bertucco:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Maurizio Fermeglia:** Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, 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.

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