Editorial
An Overview of Advances in CO$_2$ Capture Technologies

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CO$_2$ emissions generated by human activities reached the highest ever annual level of 36.3 Gt in 2021, due to the extremely rapid growth of the energy demand observed after the COVID-19 crisis [1]. There is a consensus to consider CO$_2$ (the main greenhouse gas emitted into the atmosphere) a great contributor to climate change [2]. In a scenario where the demand for energy is expected to increase by 15% by the middle of this century [3], the predominant use of fossil fuels will continue in the coming decades, especially in certain industrial sectors, in order to avoid excessive disruption to the existing energy supply chain that could negatively affect the global economy [4].

A substantial CO$_2$ emission abatement is urgent to meet the global climate targets agreed in the Paris Agreement aimed at limiting the global temperature increase to only 1.5–2 °C above pre-industrial levels [2]. Apart from the development of renewable energy sources, switching to lower carbon alternatives, or the improvement of energy efficiency in existing processes—such as CO$_2$ Capture and Storage (CCS) or Utilization (CCU)—should play a key role in the successful transition towards deep decarbonization of the global production system [5]. It has been estimated that CCS/CCU should contribute to reducing about one third of overall CO$_2$ emissions by 2050 [2], but CO$_2$ capture technologies are being developed slower than desired due to technological, infrastructural and policy barriers. As a result, most of these technologies are still relatively far from being implemented at a commercial scale at present [6,7].

Basically, in all CO$_2$ capture technologies the objective is to separate and concentrate CO$_2$ generated in stationary emissions sources, such as power generation plants or industrial processes (e.g., steel mills, refineries, cement plants, etc.). Despite the great progress made over the last decade to reduce the energy penalty and capital cost in these technologies [8–11], CO$_2$ capture is still the most demanding step (around 70% of the total cost) of the complete chain of processes required to permanently store CO$_2$ or to use it as a feedstock for subsequent chemical transformation [7].

CO$_2$ capture technologies can be classified into three groups: post-combustion, pre-combustion and oxy-combustion processes. In post-combustion systems, the CO$_2$ is removed from flue gases generated in previous fuel combustion. These flue gases typically contain a relatively low concentration of CO$_2$ (between 5 and 15% vol.), which makes it necessary to operate with a great volume of gases, leading to a large equipment cost. The separation of CO$_2$ from highly diluted gases is typically carried out using chemical solvents that require a large amount of energy for their regeneration [12]. In pre-combustion systems, the carbonaceous fuel is converted into syngas through steam reforming, gasification or partial oxidation, which is followed by a water-gas-shift reaction to obtain a mixture of H$_2$ and CO$_2$ at high pressure (i.e., between 20 and 50 bar). Then, CO$_2$ is separated, and the resulting H$_2$ can be used as carbon-free fuel or as clean feedstock for the production of ammonia, methanol or synthetic fuels. The concentration of CO$_2$ in the gases before its separation is significantly higher (i.e., 15–60% vol.), which allows for more compact CO$_2$ capture equipment. The higher starting CO$_2$ concentrations could allow the use of solvents (e.g., physical absorption) that typically demand lower energy for regeneration [13]. Finally, in the oxy-combustion systems, the fuel is burnt with almost pure oxygen rather than air,

which results in virtually 100% of CO_2 and avoids costly CO_2 purification steps downstream. However, air separation to produce pure O_2 requires high energy consumption, and strict safety procedures are needed to avoid air infiltration during oxy-combustion [14].

Currently, the industrial sector accounts for around 20% of overall CO_2 emissions, and about 70–80% of these emissions come from energy intensive industries, such as steelmaking, cement manufacture, chemical sector or paper manufacture [15]. Therefore, the decarbonisation of these industries is essential to reach the climate neutral targets in the coming decades. Some developed countries are implementing climate-positive solutions in order to drastically reduce the emissions of CO_2 into the atmosphere. Nurdiawati and Urban [15] show the substantial decarbonisation efforts planned in Sweden to achieve a deep reduction in greenhouse gas emissions by 2050, by means of great financial and political support. Numerous R&D programmes are focused on promoting renewable energies, circular economy and CCUS technologies. A good example is the HYBRIT project, in which the main Swedish steel producer leads the production of H_2 from renewable sources, which is subsequently used as a reducing agent of iron ore (instead of coke) to obtain sponge iron [16]. A recent supply chain analysis reported by Karlsson et al. [17] for the Swedish building and construction sector reveals that the implementation of energy efficiency measures, promotion of biofuels usage, renewable electrification and CCS in primary steel and cement production may lead to almost zero emissions of CO_2 by 2045. Australia presents a different situation, as its power system is dominated by the use of coal, although there is great potential for the expansion of renewable energies. Aboumahboub et al. [18] developed a comprehensive multi-sectorial model to evaluate the capacity of Australia's energy system to drastically reduce its dependence of fossil fuels in the short-to-medium term. Their results indicate that the transition to a low-carbon scenario to comply with the Paris Agreement makes necessary the rapid replacement (in less than 20 years) of coal-fired power generation through the combination of solar photovoltaic and wind energies, as well as the electrification and use of hydrogen in energy-intensive industry sectors.

Amine-based chemical absorption is currently the most technically mature CO_2 capture technology. However, this process, typically proposed as a post-combustion technology, still presents serious challenges for its commercialization, such as the high energy demand (about 4 GJ/t CO_2), the tendency of solvent degradation in the presence of SO_X and/or NO_X and the high cost of high-performance amines [7,12,19]. Alternative chemical solvents are being developed to increase the CO_2 sorption capacity at a lower cost. Ethylenediamine (EDA) is a promising solvent, less corrosive, with a higher capacity for the capture of CO_2, and it consumes less energy for regeneration than conventional alkanolamines such as monoethanolamine (MEA) [20]. The combination of post-combustion with MEA absorption in biomass-fired power plants and the subsequent storage of CO_2 in geothermal systems appears as a feasible negative CO_2 emissions option, as the calculated energy penalty is limited to 6 MJ/kg CO_2, and the estimated cost for the CO_2 avoided is around 50 EUR/t CO_2 [21].

As mentioned above, another CO_2 capture pathway that has reached a significantly high technology-readiness level (TRL) is oxy-fuel combustion. Recent studies have focused on solving the existing limitations of this technology. Ahn and Kim [22] demonstrated the feasibility of introducing flue gas recirculation (FGR) in a 0.5 MW boiler, in order to stabilize the flame generated through the fuel combustion in O_2-enriched atmospheres, while the generation of NOx was considerably reduced. As a result of that, flue gases with more than 90% of CO_2 can be obtained.

Although pressure swing adsorption (PSA) is a well-known technology for the separation of CO_2, there is great interest in developing advanced materials with improved CO_2 sorption capacity and selectivity. Cheng et al. [23] use a high-performance zeolite to study the adsorption of CO_2 from a flue gas in three consecutive beds, in order to achieve separated streams of CO_2 and N_2 with gas purity above 90%. Modelling and experimental results demonstrate that the proposed PSA configuration is able to reach the targeted gas purities with a moderate energy consumption of 1.2 GJ/t CO_2. The use of modified zeolites

to improve the CO_2 capture and/or reduce the cost of the sorbent is also a subject of study. Coal fly ash zeolites appear as an attractive option in order to use this typical waste of fuel combustion instead of its disposal. Laboratory tests for CO_2 adsorption onto this type of material show promising results (about 123 mg/g of sorbent) operating at temperatures around 60 °C, and subsequent regeneration at about 150 °C [24].

Among the emerging CO_2 capture technologies, calcium looping offers a competitive energy efficiency and moderate cost for the removal of CO_2 in both pre-combustion and post-combustion systems [13]. Recent studies demonstrate the beneficial effect of CaO (supported over iron oxide) in the gasification of biomass, not only to separate CO_2 from the product gas, thereby increasing the production of H_2, but also for the removal of the HCl generated during the gasification [25]. Calcium looping can also be applied for thermochemical storage thanks to the cyclic carbonation and calcination of calcium-based materials. In these systems, the energy required for the process (i.e., for the calcination of $CaCO_3$ that is highly endothermic) is supplied from intermittent renewable sources that are able to provide high-temperature heat (e.g., solar). When energy production is needed, the resulting CaO obtained from the calcination is carbonated, generating high-quality heat at temperatures between 600 and 750 °C. A recent techno-economic study revealed that this type of calcium looping system is able to produce electricity at prices ranging from 140 to 20 USD/MWh for energy inputs of between 50 and 1000 MW, while the CO_2 capture cost ranges from 45 to 27 USD/tCO_2-captured [26].

Conflicts of Interest: The author declares no conflict of interest.

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