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Review

# A review on solid adsorbents for carbon dioxide capture

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ABSTRACT

Global warming is considered as one of the great challenges of the twenty-first century. $CO_2$ capture and storage (CCS) technology is attracting increasing interest to reduce the ever-increasing amount of $CO_2$ released into the atmosphere and its impact on global climate change. $CO_2$ capture process is a core technology, and accounts for 70–80% of the total cost of CCS technologies. $CO_2$ capture technologies are categorized as post-combustion, pre-combustion, and oxy-fuel combustion. Among these, post-combustion $CO_2$ capture processes are regarded as being important green and economic technologies. It is very important to develop new, highly efficient adsorbents to achieve techno-economic systems for post-combustion $CO_2$ capture. In this review, we therefore summarize dry solid adsorbents, which are divided into non-carbonaceous (e.g., zeolites, silica, metal-organic frameworks and porous polymers, alkali metal, and metal oxide carbonates) and carbonaceous materials (e.g., activated carbons, ordered porous carbons, activated carbon fibers, and graphene), with a focus on recent research.


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## Introduction

### *Global warming and carbon economy*

Humans are endangered by global warming caused by the greenhouse effect. The greenhouse effect can be attributed to an increase in the emissions of greenhouse gases such as carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), chlorofluorocarbons, and sulfur hexafluoride ($SF_6$) since the beginning of industrialization. The average world temperature has increased by 0.74% in the past 100 years and is expected to increase by another 6.4% by the end of the twenty-first century [1,2].

Global warming leads to droughts, floods, heat waves, and destruction of ecosystems, and the economic loss due to climate change is expected to be 5–20% of the world's gross domestic product. $CO_2$ is a major greenhouse gas and is the main cause of global warming [3,4].

Major sources of $CO_2$ emissions are thermoelectric power plants and industrial plants (such as steel mills and refineries), which account for approximately 45% of global $CO_2$ emissions. According to a report in 2013 by the International Energy Agency (IEA), the global atmospheric $CO_2$ concentration has increased from a preindustrial value of ~280 parts per million by volume (ppmv) to ~394 ppmv in 2012. Most of the $CO_2$ emissions into the atmosphere originate from the combustion of fossil fuels (~99% of global annual $CO_2$ emissions of approximately 32 Gt) [5]. The IEA and the Organization for Economic Co-operation and Development (OECD) forecast that $CO_2$ capture and storage (CCS) could take care of approximately 14%, the expected reduction in volume of $CO_2$ emission potentials [6]. Furthermore, the Intergovernmental Panel on Climate Change (IPCC) reported that it would be possible to achieve a more than 50% reduction in $CO_2$ emissions from 2009 levels by 2050. According to their model for estimating $CO_2$ capture potential, it is estimated that 30 billion tons of $CO_2$ can be captured and stored within the European Union (EU) by 2050. Globally, 240 billion tons of $CO_2$ could be captured by 2050 [7]. Without CCS technology, the cost of meeting a 50% global reduction target by 2050 will be 70% higher [8].

Because of these global concerns, strict global regulations of $CO_2$ emissions to the atmosphere have been imposed. With enforcement of the Kyoto Protocol, there has been increased interest in the atmospheric residence time of $CO_2$ and its contribution to the greenhouse effect, and self-reduction techniques for $CO_2$ generation rates and post-treatment of $CO_2$ have received significant attention [9,10]. Various industries need to deal actively with these regulations in order to survive. CCS has great potential to be one of the more important green technologies in the future.

There is an urgent need to develop $CO_2$ reduction technologies, and we believe that CCS is the main technology that can reduce $CO_2$ emissions from the energy sector. However, with the exception of developed countries, there is very little concern about, and investment in, developing CCS. Fortunately, the world is now paying more attention and aggressive efforts are being made to commercialize CCS [11–13]. A global CCS market has begun to develop, along with certified emission reductions. The IEA/OECD, EU, and United States forecast that the CCS market will grow to its full capacity by 2020, and there is a need to obtain better insights into the techno-economic possibilities of $CO_2$ capture.

### *$CO_2$ capture and storage (CCS)*

The basic concept of CCS is to capture $CO_2$ emissions without releasing them into the atmosphere; they include sequestration or storage, as shown in Fig. 1. CCS is the process of capturing and compressing $CO_2$ generated by existing large sources of high-density $CO_2$, transporting and depositing it safely in the ground or an ocean-bedrock sediment layer, and long-term monitoring [14–16]. Transportation of $CO_2$ refers to transporting captured and compressed $CO_2$ to a storage site *via* a pipeline or other means of transport [17,18]. Storage of $CO_2$ includes post-management: the observation and prediction of the movement of the bedrock layer after $CO_2$ storage and evaluation of its effect on the environment, and evaluation of the bedrock layer's characteristics for depositing captured $CO_2$ (basins, oilfields, etc.) in the ground or below the sea [19,20]. Technologies for capture, transportation, and storage of $CO_2$ are summarized in Table 1.

All the above processes are called CCS. In addition, CCS technologies allow the continuing usage of fossil fuels and stabilize the density of greenhouse gases. Moreover, CCS may decrease the total cost of $CO_2$ reduction and offer different ways to reduce $CO_2$ emissions [21–23]. CCS is a comprehensive technology for direct reduction of $CO_2$ using the above-mentioned processes.

## $CO_2$ capture technology

### *Classification of $CO_2$ capture technology*

$CO_2$ capture is a core technology and accounts for 70–80% of the total costs of CCS technologies. It is classified at (i) post-combustion, (ii) pre-combustion, and (iii) oxy-fuel combustion

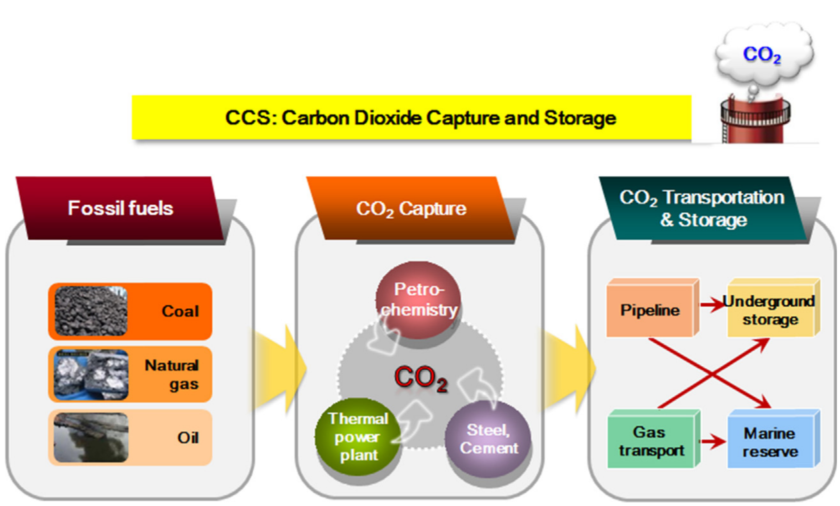


**Fig. 1.** Concept and summary of $CO_2$ capture and storage (CCS).