



# Editorial: The Role of Carbon Capture and Storage Technologies in a Net-Zero Carbon Future

Mai Bui<sup>1,2\*</sup>, Matteo Gazzani<sup>3</sup>, Carlos Pozo<sup>4</sup>, Graeme Douglas Puxty<sup>5</sup> and Salman Masoudi Soltani<sup>6</sup>

<sup>1</sup>Centre for Environmental Policy, Imperial College London, London, United Kingdom, <sup>2</sup>Centre for Process Systems Engineering, Imperial College London, London, United Kingdom, <sup>3</sup>Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, Netherlands, <sup>4</sup>Department of Chemical Engineering, Universitat Politècnica de Catalunya, Barcelona, Spain, <sup>5</sup>CSIRO Energy, Newcastle, NSW, Australia, <sup>6</sup>Department of Chemical Engineering, Brunel University London, Uxbridge, United Kingdom

**Keywords:** CCS, net zero emissions, CO<sub>2</sub> removal, BECCS, direct air capture, hydrogen, industrial decarbonisation

## Editorial on the Research Topic

### The Role of Carbon Capture and Storage Technologies in a Net-Zero Carbon Future

Carbon capture and storage (CCS) technologies are recognized as having an important role in providing a cost-effective approach to limit global warming to 1.5°C (IPCC 2014; IPCC, 2018). The transition towards net-zero CO<sub>2</sub> emissions will present technical, economic, commercial and policy challenges for the deployment of CCS and CO<sub>2</sub> removal technologies. The opportunities for deployment will be diverse, and will significantly depend on the specific conditions found in the different regions of the world. Factors like national policies, availability of local resources, infrastructure and economy features, breakdown of GHG emissions across sectors, and societal background and wealth will all interplay to create conditions that are either favorable or disadvantageous to the deployment of CCS. This special issue is a collection of articles that explore the role of CCS and CO<sub>2</sub> removal technologies in delivering reductions to CO<sub>2</sub> emissions for a net-zero carbon future. The collection of publications includes two reviews and six original research articles, which are summarized below.

Johnsson et al. maps the potential costs associated with integrating CCS into all industrial manufacturing plants in Sweden, illustrating the marginal abatement cost curve (MACC). This helps quantify the level of decarbonisation required and identify the types of CO<sub>2</sub> point sources, e.g., fossil fuel CO<sub>2</sub>, or biogenic CO<sub>2</sub>. The study evaluated the CO<sub>2</sub> capture costs of 28 plants in Sweden, including a petrochemical site, refineries, iron and steel plants, cement plants and pulp and paper mills. These plants generate >500 kt CO<sub>2</sub> of the annual emissions, which is >50% of Sweden's total CO<sub>2</sub> emissions from all sectors. The marginal abatement cost curve showed capture costs ranging between 40 and 110 €/t CO<sub>2</sub>, depending on the emission source, and includes the cost of transport and storage (adds 25 to 40 €/t CO<sub>2</sub>). Based on this type of analysis, a national strategy towards net-zero across the industrial sector could be developed, identifying the low-cost CO<sub>2</sub> capture options and opportunities for cost reduction.

Hydrogen and electrification are possible strategies for the decarbonisation of industrial clusters. Herraiz et al. proposes a system that uses steam methane reforming (SMR) for hydrogen production and power generation with CCS. An integrated system with SMR and power plant with CCS was found to produce 696,400 Nm<sup>3</sup>/h of H<sub>2</sub> with a net power output of 651 MWe at a net thermal efficiency of 38.9 %<sub>LHV</sub>. The authors also present new insights for the design

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### Edited and reviewed by:

Uwe Schroder,

Technische Universität Braunschweig,  
Germany

### \*Correspondence:

Mai Bui  
m.bui@imperial.ac.uk

### Specialty section:

This article was submitted to  
Carbon Capture, Utilization and  
Storage,  
a section of the journal  
Frontiers in Energy Research

**Received:** 30 June 2021

**Accepted:** 08 September 2021

**Published:** 17 September 2021

### Citation:

Bui M, Gazzani M, Pozo C, Puxty GD  
and Soltani SM (2021) Editorial: The  
Role of Carbon Capture and Storage  
Technologies in a Net-Zero  
Carbon Future.  
Front. Energy Res. 9:733968.  
doi: 10.3389/fenrg.2021.733968

and operation of reformers integrated with gas turbines and CO<sub>2</sub> capture, demonstrating methods to improve efficiency.

There are also opportunities to deploy new technologies in the power sector. Wevers et al. evaluates the potential of Power-to-Fuel-to-Power systems in delivering net-zero GHG emissions in energy systems, also considering the life cycle assessment (LCA) of environmental impacts. For comparison, another system generating electricity from natural gas combustion with 100% carbon capture and storage is also evaluated. Of the different Power-to-Fuel-to-Power systems, the hydrogen storage system had the lowest environmental impact in all categories. This study highlights the importance of LCA studies in identifying any negative environmental impacts associated with the deployment of new technologies.

Addressing the issue of high costs for technologies that remove CO<sub>2</sub> from air is a key challenge. The techno-economic study by Kiani et al. identified key areas of possible performance improvement with conventional absorption-based direct air capture (DAC) using monoethanolamine (MEA). The energy consumption of MEA-based DAC was found to be a function of key process parameters, including air humidity, CO<sub>2</sub> capture rate, CO<sub>2</sub> loading of the lean and rich amine and reboiler temperature. The base case MEA scenario resulted in a reboiler duty of 10.7 GJ/tCO<sub>2</sub> and an electrical energy requirement of 1.4 MWh/tCO<sub>2</sub>, corresponding to a capture cost of \$1,691/tCO<sub>2</sub>. The overall cost range of the DAC process was between \$273–1,227 per ton of CO<sub>2</sub>, varying with different economic parameters. The study found that significant cost reductions could be achieved with the use of low-cost materials, innovative absorption contactor, which operates at lower liquid-to-gas ratios, and an absorbent with low volatility to avoid a water wash.

In the case of bioenergy with CCS (BECCS), the cost of transporting biomass can represent a significant proportion of the final biomass price, and there will be costs associated with CO<sub>2</sub> transport. Stolaroff et al. assessed the transport costs associated with BECCS projects using data for the United States. The cost-optimal combination of transport for each scenario was a function of the transport capacity and distance. Biomass transport by rail is the most competitive option for systems capturing and storing most of the biogenic CO<sub>2</sub>, e.g., gasification to hydrogen or combustion for electricity generation. For large projects storing >1 Mt/yr CO<sub>2</sub> or transporting CO<sub>2</sub> > 1,000 km, the lowest cost option for CO<sub>2</sub> transport is pipeline. In contrast, CO<sub>2</sub> transport by rail is more cost competitive for smaller BECCS projects. In cases where developers have flexibility to choose the BECCS project type and transport modes, the transport costs were between \$20–40/tCO<sub>2</sub> stored for projects with distances of hundreds of kilometers from the biomass source to the storage site.

Scenario-based assessments are particularly useful in identifying deployment hurdles and opportunities at a systems scale. The systematic review of 66 German energy and decarbonisation scenarios by Hahn et al. identifies “blind spots” in regards to scenario assumptions around BECCS technology options and

applications. The review reveals that future scenario analyses need to incorporate other considerations, including a framework for land use change and emissions accounting (only considered in ~10% of scenarios), as well as the impact of public acceptance on technology deployment.

Another key consideration highlighted by Fuss and Johnsson is that scenarios need to consider the technology deployment rate as well as ensure that the ramp-up in deployment is achievable. The conditions for BECCS in Sweden are particularly favorable due to the existing large point sources of biogenic CO<sub>2</sub> emissions in the country. Despite the favorable conditions, the current deployment rate of BECCS is limited. To achieve Sweden’s net-zero target by 2045, two ramp-up scenarios for BECCS were proposed. The study reveals that immediate introduction of political and economic incentives would likely be required to significantly accelerate deployment to the levels required for the target.

A review and analysis of the status and possibilities of CCS deployment in the Netherlands by Akerboom et al. indicates there are no significant technical challenges. Historically, CCS deployment has mainly been hindered in the Netherlands by the lack of a compelling socio-technical narrative. Owing to the shift in focus from power to industry, CCS is now deemed vital in the transition to net-zero, offering the means to rapidly reduce CO<sub>2</sub> emissions significantly. The narrative around CCS is more favourable. The prospects of CCS have also appeared to improve since the introduction of new financial mechanisms, as well as increased government support and social engagement. Fit-for-purpose legal frameworks and policy instruments will likely have an important role.

## AUTHOR CONTRIBUTIONS

MB was the primary author of the Editorial. MG, CP, GP, and SS provided feedback and contributions to the paper.

## FUNDING

The authors would like to acknowledge funding from the Research Councils UK under grants EP/N024567/1 (CCS from Industrial clusters and their Supply chains), NE/P019900/1 (Comparative assessment and region-specific optimisation of GGR) and EP/T033940/1 (Multiphysics and multiscale modelling for safe and feasible CO<sub>2</sub> capture and storage).

## ACKNOWLEDGMENTS

The authors would like to thank and acknowledge Angel Galan Martín from the Universidad de Jaen in Spain for contributing to the development of this Research Topic. CP is a Serra Hunter Fellow.

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