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S. Societal Impact

Enhancing technological innovation in the transition to net-zero. Carbon Capture, Usage and Storage.

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Wioletta NAWROT & Tomasz WALKOWICZ
ESCP Business School

ESCP RESEARCH INSTITUTE OF MANAGEMENT (ERIM)

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Wioletta Nawrot*
Tomasz Walkowicz

ESCP Business School

Abstract

When the Carbon Capture, Usage and Storage (CCUS) technologies move to mainstream, they can facilitate the transition to net-zero while helping to ensure energy security. The aim of this article is to analyse the challenges to the expansion of CCUS and to reflect on how they can be addressed. The main issues identified include high costs, insufficient technological performance, and environmental risks. However, continued technological innovation should effectively remove those constraints and enable a broad adoption of CCUS. Some governments have already launched initiatives aimed at strengthening and dynamising the investment in CCUS development. Despite this, a broader policymaker support for further technological development, deployment and operation is urgently required for CCUS to serve as an effective climate solution.

Keywords: Carbon Capture, Usage and Storage (CCUS), climate agenda, net-zero

*Associate Professor

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Importance of CCUS for climate and energy security

Carbon Capture, Usage and Storage (CCUS) technologies enable the reduction of carbon dioxide (CO2) emissions from large, polluting industrial facilities and / or the removal of existing CO2 from the atmosphere. Climate scientists claim that it is impossible to reach net-zero targets without CCUS deployment on a wide global scale and several organisations, including the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) advocate an effective acceleration of CCUS globally if we are to reach climate targets.

There are different methods of capturing CO2 in the production process (through equipment fitted to new plants or retrofitted to existing plants): post-combustion, pre-combustion and oxy-fuel combustion being the most important, while the direct air capture technology with industrial fans is used to capture CO2 directly from the atmosphere. The captured CO2 is compressed into a liquid, which can be transported and injected into deep geological formations of underground storage, in saline aquifers as an example, or in existing or depleted oil and gas reservoirs. Every high-emitting nation has its own ample natural storage facilities. The captured CO2 can be also used as an input in the production of commercial goods, for example carbonates, beverages, building materials, but this is still a niche application of captured carbon.

An acceleration of the deployment of CCUS technologies would effectively support the transition of economies to net-zero and enhance energy security, especially in times of significant geopolitical reconfigurations. Not only can CCUS help in decarbonising the most polluting industries (iron & steel, cement, chemicals, fertiliser) and countries and in capturing existing carbon dioxide from the atmosphere but it also provides a source of low-carbon power generation.

Moreover, converting the fossil fuel into a gaseous mixture of hydrogen and CO2 before it is burnt during CCUS (pre-combustion method) allows the usage of hydrogen as a source of energy of various applications after carbon dioxide is set to be permanently removed.

CCUS installations are primarily designed to operate in big industrial facilities, but this technology can also potentially be adapted for wider household application. Low-carbon hydrogen has potential to decarbonise both domestic and industrial heating and transport.

Challenges

To effectively support the deployment of CCUS on a wide global scale, several challenges need to be addressed.

High cost of CCUS technologies and operation

CCUS facilities are capital-intensive to deploy and energy-intensive / expensive to operate. The cost of CCUS applications can vary greatly depending on the CO2 source, with lower costs for the ethanol production or natural gas processing (highly concentrated CO2 streams) for example and much higher costs in cement production and power generation (less concentrated CO2 streams) for example. Capturing carbon dioxide directly from the air is currently the most expensive process. Costs also vary depending on the stage of development of the different CO2 capture technologies.

However, the cost of CCUS is gradually decreasing, especially for large-scale CCUS projects. According to the Global CCS Institute, in 2022 alone 61 new CCUS projects were initiated globally. In total there are already 30 CCUS projects in operation, 11 under construction and 153 in development. The US has a greater number of CCUS facilities than any other country, but many other countries are increasingly looking at including CCUS into their climate protection efforts and this in turn should bring costs down. IEA estimates show that in large-scale CCUS facilities the cost of CO2 capture in the power sector has been already reduced by 35% through its evolution from the first to the second large-scale CCUS facility.

Even if CCUS facilities are still very expensive to deploy and operate, for the industries that struggle most with achieving necessary emissions reductions due to the specifics of their production process and their tangible assets' long life-cycle, employing even the most expensive today CCUS technologies can be cheaper than other available alternatives. For heavy industry for instance CCUS is a relatively advanced and cost-competitive option if we are to reach the climate targets set in the Paris Agreement (Baylin-Stern and Berghout 2021). According to the IEA, CCUS is critical for cement production where, due to the source of the CO2 emissions, CCUS currently appears to be the only effective solution for reducing emissions. CCUS is also the most advanced and least costly low-carbon option for the iron and steel sector - it raises estimated costs by less than 10%, while approaches based on electrolytic hydrogen can raise costs by 35-70% compared with today's conventional production methods. Similarly, the deployment of CCUS raises costs by 20-40% in the production of some important chemicals while the next best alternative - an electrolytic hydrogen method is estimated by the IEA to be 50-115% more expensive.

Moreover, the cost assessment of CCUS development, deployment and operation cannot be carried out without considering the wider economic benefits in the future. Indeed, in the most restrictive future climate protection needs scenario, CCUS application could even prevent the most energy-intensive industries from being halted to stay compliant with the climate targets. This shows the very important role CCUS must play in reaching net-zero by 2050.

Insufficient technological performance of CCUS

As CCUS are still considered technologically young, CCUS operations are not free of concerns. One of them is the technological underperformance of CCUS operations. One of the recent assessment studies of the technological performance of CCUS projects by the Institute for Energy Economics and Financial Analysis demonstrated that several schemes covering together over half of captured carbon dioxide worldwide have either failed entirely or captured significantly less carbon dioxide than they were designed to capture (Robertson et Mousavian, 2022). As an example, ExxonMobil's La Barge facility at Shute Creek in Wyoming performed approximately 36% below its expected level, when the world's only large power station with CCUS, Boundary Dam in Saskatchewan, Canada, underperformed by about 50%. These examples suggest that the deployed CCUS technologies are not yet reliable.

Particularly challenging due to the problems with water pressure are CCUS that, unlike systems using depleted oil or gas wells as CO2 storage, utilize saline aquifers free of fossil fuels. One of the examples is the Gorgon - Chevron Corp.'s flagship project in Australia, operating at around one-third of its intended carbon capture capacity. Complex solutions are being considered by the firm to improve its performance, one of them being the removal of water and transfer of it into another reservoir nearby to allow CO2 to be injected at a higher rate. An additional significant investment into the project is necessary.

Environmental risks

One of the main risks of the CCUS operations are CO2 leakages from storage, causing environmental damages instead of offering a climate protection solution. However, these concerns might be exaggerated as natural geological formations that serve as a storage for CO2 have already stored gas and carbon dioxide naturally for millions of years.

The CCUS literature also highlights that CCUS systems increase environmental damages from toxicity, acidification, eutrophication, etc. But it also concludes that there is a net environmental benefit if we compare the reduced environmental damage from climate change achieved by CCUS systems with environmental and health damage induced by CCUS itself. As an example, Singh et all (2012) estimated that CCUS offers a net reduction of 60-70% in human health damage and 65-75% in ecosystem damage. More research needs to be done to further explore the environmental risks of CCUS systems.

Usage / disposing of captured CO2 as an input for commercial goods and services / recycling of CO2 is also advancing but the more complex climate implications of such applications are still under examination.

From a climate point of view, a controversial form of utilisation of captured CO2 is Enhanced Oil Recovery (EOR), a 50-year-old technology that relies on captured carbon in the process of producing oil and gas. Carbon is captured and sold as a commodity to oil companies who, by pumping it into their depleted oil and gas fields, enhance their hydrocarbon production and push more oil out of the wells. On the Global CCS Institute 2022 Facilities List, approximately one fifth of facilities reuse CO2 in EOR processes. In terms of total carbon capacity, this translates into EOR projects using about 73% of the total carbon dioxide captured each year globally in the past years, while only approximately 27% is being stored in deep natural geological formations and only a negligible percentage is recycled.

Addressing the challenges

The main identified challenges to the expansion of CCUS have to do with the high costs, insufficient technological performance, and environmental risks. Many aspects of these challenges can be effectively addressed by boosting innovation, which is key to fostering new CCUS technologies and advancing existing ones. Some CCUS technologies are commercially available, but more progress is needed to improve their performance and reduce costs, when other CCUS technologies are still in development. According to the IEA, while we are able to cut a large amount of emissions with the technologies currently available, they are insufficient on their own to bring us to net zero and simultaneously ensure energy security. 60% of cumulative emissions reductions (by 2070) seen in the IEA's 'Sustainable Development Scenario' come from technologies that are currently in the earliest stages in the clean energy innovation pipeline: 'prototype' or 'demonstration' phase whereas a relatively lower share of emission reductions come from technologies that are in the stage of 'early adoption'. When it comes to CCUS, there are still no technologies considered in the 'mature' stage. It is expected that a cost and performance gap (with established technologies) which still exists in the 'early adoption' stage will be closed when we move to the 'mature' stage, i.e. when the deployment of CCUS moves to the mainstream.

In turn, the pace of innovation will depend on the involvement of various stakeholders and the policies governments introduce today.

Necessary public and private investment in R&D

CCUS solutions will not become available at scale without further significant public and private investment in R&D. Government support of CCUS innovation is needed even more after the Covid-19 pandemic caused an unanticipated setback in clean energy innovation, and - according to an IEA survey - a reduction in the R&D budgets of net-zero emissions technology companies. A further investment to boost performance of the existing CCUS systems is also necessary.

Judging from the experience of the past few decades of the expansion of the renewable energy technologies, the more R&D advances and practical know-how accumulates, the more dynamically the CCUS market will grow, economies of scale be reached, and the cost of financing fall. There is also potential to reduce costs along the CCUS value chain. As an example, 70 years of continuous cost reductions for solar PV were due to governments (especially the US, Germany, and China) successfully using R&D and market-pull policies (including targets and revenue guarantees), to stimulate investments all along the value chain that supported innovation and economies of scale (IEA 2020).

Building or improving the CCUS infrastructure

Governments also need to assist with legislation, funding and incentives to **build or improve the CCUS infrastructure**. The development of carbon dioxide storage in geological formations other than used by EOR existing fossil fuel reservoirs and of CO2 transport infrastructure is key. This would facilitate a shift of the CCUS applications towards more environmentally friendly and permanent removal of carbon dioxide from industrial facilities and the atmosphere and support clean energy generation.

Scalable infrastructure models for CCUS and the need for shared CCUS infrastructure on a regional, national and international scale has been discussed in the literature for long time (see Middleton and Bielecki, 2009) but no satisfactory progress has been achieved yet. Developing CCUS infrastructure in industrial clusters is especially beneficial as it could generate important (external) economies of scale. Increased efforts on expanding CCUS cross-border should follow, but in this case more legal and practical challenges need to be tackled; the most pressing issues are those surrounding transboundary regulation and legal frameworks in support of the development of CCUS transnational networks.

CCUS as legal requirement for some industries

Also, once CCUS technology becomes mainstream, reaching the ‘mature’ stage in the clean energy innovation scale, in coordination with other **countries, governments need to consider making carbon capture, usage, and storage a legal requirement for the most polluting industries.** Under the assumption that government support for CCUS innovation significantly accelerates and as a result the advanced CCUS technologies are available by 2030, it would be sensible to start policy consultations with the industry and other stakeholders as soon as possible, with 2030 as the target date for regulation to come into force. Advance planning would give governments and industry enough time to incorporate the requirements of this climate legislation into their budgets and long-term business models and to prepare operationally and financially.

Strengthening the regulatory framework and governmental policy

The regulatory framework for CCUS and relevant governmental policy are key to the acceleration of the scaling-up of CCUS and need to be adapted to country / regional / sector-specific needs, (ideally) in co-operation with other nations and globally coordinated. Sharing best practices, R&D resources and addressing technology challenges in a global forum would be the most effective way of advancing CCUS innovation and deployment. Governments need to ensure that advanced CCUS technologies are available by 2030, if we are to reach net-zero objectives.

A list of over 20 countries with legal and regulatory CCUS foundations already in place is growing, with significant global policy, legal and regulatory developments over the past years.

Even if some governments, especially in North America, Europe and the UK have been actively supporting the investment in CCUS development and deployment, much more needs to be done, and urgently so, by policymakers and more countries need to join for CCUS to serve as an effective climate solution.

The US is taking the lead in CCUS policy with a recent US$62 billion budget for the US Department of Energy prioritising investments in clean energy (the Infrastructure Investment and Jobs Act of 2021). These provisions created opportunities to accelerate the deployment of carbon management activities, both to mitigate and reduce carbon dioxide emissions. Also, with close to US$370 billion in incentives for clean energy and climate-related spendings, the Inflation Reduction Act of 2022 provides significant benefits for the carbon capture industry around the US. It expands the availability of federal income tax credits for CCUS projects, extending the start of their construction timing, lowering capture thresholds, etc. At the same time, at state level, the law has started to give more attention to CCUS deployment and operation, in which to store carbon, with California, Pennsylvania, West Virginia and North Dakota being the most advanced.

Canada has followed the US lead, recently establishing their own C$2.6 billion tax credit budget for CCUS projects.

In Europe, Denmark has earmarked €5 billion in subsidies for CCUS and Norway has granted a NOK1 billion (US$100 million) budget to support blue hydrogen projects.

The first two calls of the European Union's Innovation Fund also seem to be supportive of CCUS projects as up to date 11 approved projects include a CCUS component: low-carbon cement production as an example, bioenergy with carbon capturing facility, carbon mineral storage site development and sustainable aviation fuel production. This year's third call has seen a significant increase in the European Commission funding, with a planned €3 billion investment in clean tech projects.

Also, the UK government has advanced their support for CCUS. The 'Carbon Capture, Usage and Storage Net Zero Investor Roadmap' outlines the UK government and industry's joint commitments to the national deployment of CCUS. The UK government aims to support the establishment of two CCUS low-carbon industrial clusters by mid-2020s (selected East Coast and HyNet) and a further two by 2030, which are expected to capture 20-30 MTCO2 per year by 2030. Included in the incentives package is a £20 billion investment in the early deployment of CCUS, including the £1 billion CCUS Infrastructure Fund to support the capital costs of strategic CCUS projects. Another aspect of the same plan is the Industrial Decarbonisation and Hydrogen Revenue Support scheme to fund business models for low carbon hydrogen production and industrial carbon capture that offers investors the long-term revenue certainty they require.

Outside North America and Europe, other countries are also advancing their CCUS policies. As an example, A$200 million in funding to support CCUS has been made available in Australia, along with approving a method to allow the creation of Australian carbon credits and releasing additional acreage for geological storage of carbon dioxide. The Sixth Strategic Energy Plan gives CCUS a prominent role in Japan's efforts towards net-zero, and China has approved more than 10 national policies and guidelines supporting CCUS, but other Asian countries and other continents are less advanced in developing CCUS legislation.

It is of high importance that governments place CCUS policy high on the list of their national priorities as the recent UN IPCC assessments leaves no reasonable doubt that the transition to net-zero cannot be delayed if the world is to avoid a humanitarian crisis on an unprecedented scale. Scientific evidence suggests that the climate has been changing more rapidly than previously assessed and that the effects of the interferences to the global climate system are more worrying than previously thought. Published in October the 2022 UNEP Emissions Gap Report brings further highly worrying evidence that the international community is falling far short of the Paris goals, with no credible pathway to 1.5 deg. Celsius in place. On one hand, the window for coordinated global action protecting climate is closing fast and any delay would be detrimental to the planet, on the other hand Russia's invasion of Ukraine and the consequences of the current geopolitical tensions have the potential to undermine the global sustainability agenda, which aims to ensure the continuity of energy supplies and address the cost-of-living crisis. Reassuringly, some of these challenges, especially risks to energy security, can be effectively addressed by continued investment in clean energy technologies, among which CCUS solutions, the development of which needs to be incentivised. There are already examples from the US demonstrating that governmental incentives are influencing companies' investment commitments. US companies have committed US$200bn to producing clean technology and semiconductors since President Biden's administration approved the subsidies in the Inflation Reduction Act of 2022, a double of the investments in the same sectors a year earlier. This evidence should encourage other countries to follow the US lead in supporting CCUS.

There are also studies seeking to optimise the financial support for CCUS technologies, differentiating between subsidies to develop and produce CCUS technology (an upstream subsidy) and subsidies for the purchasers of CCUS technologies (a downstream subsidy). As an example, one study that integrated in its modelling the strategic trade policy with an economic model of the European energy markets, argues that upstream subsidies should be preferred in Europe and that subsidies to CCUS coal power should exceed subsidies to CCUS gas power (Aune et al, 2022).

Policymakers must also ensure the safe deployment and operation of CCUS facilities and infrastructure to prevent any health & safety occupational risks for employees and other stakeholders as well as any risks of environmental damage.

Finally, to advance the climate agenda with CCUS being part of climate solution, Western governments need to think carefully about how the **overall formula of the profit's taxation** (with windfall taxes) is likely to impact investment by energy companies transitioning to net-zero. As an example, in the UK, in addition to the permanent 40% tax rate paid by oil and gas producers, the British windfall tax raised the combined headline tax rate for the sector to 65% by the end of 2022 and to 75% from January 2023 until March 2028. The energy profits levy included a 'super-deduction'-style relief to incentivise investment in UK oil and gas extraction to support jobs and bolster the future energy security. It also recognised efforts by energy companies towards net-zero, where the decarbonisation expenditure qualified for the highest rate of the investment allowance. However, with energy companies reporting record profits in 2022, including £23bn for BP and £32bn for Shell, governments have been pressured to charge energy producers even more, both through further increase of tax rates and the elimination of the investment allowance. This is concerning as in the context of global climate action goals, the taxation of energy producers should not come at the cost of slowing down their investments towards net-zero. With careful planning and governments working alongside with industry, it should be possible to share the burden and progress towards net-zero targets. As well as investing in renewable energy, fossil fuel extractors should contribute to climate action by disposing of carbon dioxide safely and permanently, not only engaging in EOR. Instead of introducing further changes to the taxation of energy companies governments should rather insist that the chief polluters invest in carbon capture and storage development, deployment and operation to drastically reduce their emissions. The recent record profits provide the energy sector with the ideal source of funding of these still very expensive technologies. Also worth considering, recent research from the Universities of Oxford and Edinburgh proposed a ‘carbon takeback obligation’ to prevent the fossil fuels industry from contributing to global warming. Since their activities generate a considerable amount of carbon dioxide, according to this proposal fossil fuel extractors and importers would be required to dispose of a gradually rising percentage of CO^2 both safely and permanently. The percentage in question would need to increase to 100% by 2050 (Jenkins et al, 2021).

Conclusion

A targeted shift to net-zero in line with the Paris Agreement while ensuring the energy security is dependent on technologies which are expected to emerge thanks to further investment in R&D. Climate scientists claim that it is impossible to reach net-zero targets without expanding CCUS technologies. Governments need to ensure that advanced CCUS technologies are available by 2030 to effectively support the climate agenda.

The main identified challenges include high costs, insufficient technological performance, and environmental risks. However, continued technological innovation should effectively remove those constraints and enable the broad adoption of CCUS.

A further substantial public and private investment in R&D for CCUS technologies and close policymakers’ attention are urgently needed. Governments also need to effectively support the development of the CCUS infrastructure which is essential for the transport and storage of CO2. Developing CCUS infrastructure in industrial clusters is especially beneficial as it could serve as an important source of (external) economies of scale. Expanding CCUS cross-border should be the next step but, in this case, legal and practical challenges would need to be tackled, the most pressing issues are those surrounding transboundary regulation and legal frameworks in support of the development of CCUS transnational networks. A central concern of policymakers needs to be ensuring safe operation of CCUS infrastructure to prevent any health&safety risks for employees and other stakeholders as well as any risks of environmental damage. Also, once CCUS technology is sufficiently developed, governments should consider regulations that would impose mandatory usage of CCUS by the most polluting industries.

Some governments have already launched initiatives aimed at strengthening and dynamising the investment in CCUS development. Despite this, a broader policymaker support for further technological development and deployment and operation is urgently required for CCUS to serve as an effective climate solution.

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