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IEAGHG Technical Report
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Value of Emerging and Enabling Technologies in Reducing Costs, Risks and Timescales for CCS

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VALUE OF EMERGING AND ENABLING TECHNOLOGIES IN REDUCING COSTS, RISKS AND TIMESCALES FOR CCS

(IEA/CON/18/254)

This study is a horizon scanning exercise, aiming to understand the relevance of digital and enabling technologies for CCS and to assess the benefits they could offer to the large-scale deployment of CCS. It was contracted with the consultants Element Energy who led the work in conjunction with Imperial College, London.

Diverse technologies, platforms and innovations developed outside of the energy sector are now being brought to this sector to reduce costs, risks and timescales for projects and could be applicable to current and future CCS projects as well. The deployment of CCS currently falls short of the projected capacity needed to achieve global emissions reduction targets, despite being a proven technology in the reduction of greenhouse gas emissions.

Key Messages

- There are a wide range of relevant applications for digital and enabling technologies in CCS that could potentially reduce costs and address risks and challenges in deployment.
- Although only some applications are currently under development in CCS, the benefits of these technologies discussed in the report are largely transferable from related sectors.
- Applications of artificial intelligence (AI) and internet of things (IoT) in predictive maintenance and automation deliver the greatest potential reductions in project costs.
- Significant savings are only expected to be realised from 2030.
- Additive manufacturing will have the greatest impact in capture downtime. VR (Virtual reality) and AR (Augmented reality) will primarily impact on the reduced downtime, while advanced materials are considered most applicable in storage projects.
- Total cumulative global savings of almost \$200bn (10%) in total lifetime costs of projects deployed up to and including 2040 are possible.
- Cost model projections predict that:
    - For sites operating in 2025, overall reductions of 2% in lifetime costs can be expected for onshore and offshore sites, resulting from 8-9% less OPEX (operational expenditure) costs and a reduction of 10% in supply chain losses.
    - By 2040, 19% overall cost reductions are projected in offshore projects and 26% in onshore; a result of a 7-9% CAPEX (capital expenditure) reduction, 50% OPEX reduction and 50% reduction in injection facility downtime.

Background to the Study

CCS is a proven technology that is key for achieving global climate change targets and not only does it directly mitigate emissions from industry, it also enables wider deployment of other low carbon energy technologies, such as through decarbonisation of hydrogen production by steam methane reforming. CCS needs to be implemented on a large scale in order to meet global climate change targets; however, the high capital costs and risks associated with large-scale CCS have led to delays in supply chain development. Accelerating the rate of future development is of importance and requires technological advances to support cost-effective deployment and operation. Current R&D into the reduction of costs, risks, timescales and challenges primarily focusses on conventional and established improvement processes or methods. However, emerging and enabling technologies have the potential to offer more opportunities for cost and risk reduction.

Digitalisation is expected to deliver significant improvements in safety, flexibility, efficiency and sustainability of energy systems in the future. Many emerging digital and enabling technologies are already being used to reduce costs, risks and timescales in the energy sector; with so many similarities between this sector and CCS (in terms of sites, processes and project development) it is likely that many of these applications will be transferable.

Scope of Work

The main aim of this report was to explore and identify which digital and enabling technologies may offer benefits for commercial scale CCS deployment. A wide range of these technologies were considered and broadly grouped into six categories:

- Robotics, drones and autonomous systems – common applications being monitoring and remote operation, including all independent physical systems that are used to carry out specific tasks.
- Novel sensors – common applications being subsurface analysis, CO_2 detection and condition monitoring, including improvements to existing sensing techniques and novel sensor networks and techniques.
- Digital innovations – such as digital platforms and techniques for advanced data processing, analysis and communication. This has common features like advanced analytics, smart systems, automation and optimisation, and includes the IoT, AI, simulations and block-chain.
- Virtual / augmented reality (VR / AR) – be it enhanced operation, remote operation and training applications, these techniques include immersive technologies either creating a virtual environment for the user to interact with (VR) or overlays virtual objects onto the real world (AR).
- Additive manufacturing – a suite of technologies that build up 3D objects (3D printing), allowing for rapid manufacture, bespoke design and in situ builds.
- Advanced materials – two specifically; nanomaterials and composite pipelines.

A horizon scanning exercise, complete with literature review and stakeholder interviews, was undertaken to determine the applications and possible benefits of these technologies in industries similar to CCS. Case studies were used to demonstrate their applicability. This information was then used in an assessment of the relevance and potential impact of emerging and enabling technologies on CCS. Relevant applications of applicable technologies were then defined and their quantitative impact on project costs was modelled. The qualitative impacts on potential risks and challenges in the CCS industry was also assessed and the findings were tested through engagement with external experts. The study then analysed the implications of the cost and risk reductions within the context of the expected investment required to deploy CCS on the scale necessary for achieving global climate targets, in the context of the IEA's 2°C Scenario and Global CCS Institute global cost documentation.

Findings of the Study

The findings of the horizon scanning exercise identified the main applications and benefits of each area of these emerging and enabling technologies, before looking at case studies where these technologies could benefit the area of CCS.

Main categories of emerging technologies

1. Robotics, drones and autonomous systems.

Applications of these technologies include asset monitoring, route surveying, remote repair and autonomous shipping. In asset monitoring, benefits include reduced cost, better safety and improved effectiveness of monitoring. Application to route surveying could lead to improved route appraisal, reduced time and cost. Remote repair could mean reduced man hours, cost and downtime, and autonomous shipping would benefit by reducing operational costs and leading to more efficient ship design.

In shipping tanker inspection, engineering companies have used drones operated remotely to inspect tanks, which would be a requirement for the shipment of CO_2. Along with tank inspection, drones could be applicable to a wide range of assets in the energy sector for maintenance and monitoring purposes. Pipeline repair has been carried out by inspection robots on gas pipes in London. Lower cost and less disruptive maintenance inspection is directly transferable to CO_2 pipelines, which could extend pipeline lifetime and potentially reduce the need for more expensive techniques such as pigging (pipeline inspection system). The STEMM-CCS project is developing the use of AUVs (autonomous underwater vehicles) for storage site monitoring.

2. Novel sensors

Subsurface sensing, gas sensing and corrosion sensing are the applications that could benefit from emerging technologies such as novel sensors. Benefits include reduced appraisal and storage monitoring costs, reduced loss of CO_2, avoided CO_2 tax, lower inspection costs and a reduced risk of failure.

Seismic sensing in the oil and gas industry requires cabled sensor networks across areas, meaning intensive labour time and costs. Alternative wireless sensors have been used with fast distribution and higher resolution than conventional sensors. There have been other developments in solar-powered sensors which extends the lifetime in the field and developments in sensors to detect low level (natural) vibrations, eliminating the need for manmade vibration sources. Novel sensors, once proven, would benefit the seismic analysis in the CCS industry to assist with site appraisal and ongoing monitoring, with the benefit of faster and easier deployment, better quality of data and more continuous monitoring capabilities. In-well monitoring with novel sensors are already being trialled at CCS projects to monitor storage sites with high quality, in demand imaging, leading to reduced operational costs and reduced health and safety risks. Shell’s Quest project, for example, is using InSAR satellite imaging for digital elevation assessment, distributed temperature sensing, distributed acoustic sensors and downhole microseismic techniques for monitoring CO_2 storage and well integrity. In another case the STEMM-CCS project is working on detection of potential CO_2 releases in one area of the CCS supply chain, sensing potential releases in the marine environment from subsea pipelines or control systems.

3. Digital innovations

Common applications could include: process optimisation and automation (benefitting from reduced costs, increased efficiency, reduced downtime); predictive maintenance (could lead to cheaper, more effective maintenance; lower failure rates meaning reduced downtime); predictive analysis (which would benefit from reduced development time and costs for materials / processes with emerging and enabling technologies); simulation and virtual commissioning (could see lower commissioning times and costs and improved plant operation); and verification and smart contracts (where emerging technologies could provide increased trust and reduced administrative costs).

Automation, optimisation and predictive analysis are applications highly transferable to CCS. Predictive systems in the oil and gas industry use machine learning to develop monitoring systems that detect aspects such as pump failure. The produced algorithm predictions can then be used to inform maintenance strategies, replacing routine preventative maintenance and therefore reduce operating costs. Better reservoir management is expected with the use of predictive analysis and has been applied in oil fields to identify the optimum strategies for water injection and production patterns. Similarly in CO_2 storage sites better data collection with digital innovations would enable better storage site management and better performance predictions of new sites. In addition, block-chain verification could help to verify stored carbon for compliance with storage regulations and carbon trading systems requirements by providing distributed ledgers and smart contracts to assist with low administrative burden. Imperial College London are trialling an automation system for controlling plant operation including data monitoring, engineering configuration, maintenance and safety routines. Block-chainpowered platforms for carbon trading are also currently under development for tracking and verifying carbon removal, which will help facilitate carbon removal certificate trading.

4. Virtual / augmented reality

Applications in CCS such as enhanced inspection / maintenance, enhanced design, remote operation and VR training could all benefit from emerging and enabling technologies. This would mean reduced maintenance costs / time, decreased downtime, reduced costs in design and commissioning, improved safety, plus reduced labour costs. Advantages could also include lower training costs and improved training standards.

Enhanced maintenance could result from remote operation and assistance with AR and VR in offshore operations particularly, by limiting the number of crew needed and therefore facilitating OPEX cost savings.

5. Additive manufacturing

Additive manufacturing applications that may benefit from emerging / enabling technologies include rapid prototyping (benefitting from reduced design time, cost of prototyping and initial testing), spare parts (which would lead to lower sunk capital, reduced lead time and reduced plant downtime) and component optimisation (meaning reduced maintenance and equipment costs and improved performance).

In the aviation industry, additive manufacturing has been used to improve performance and lower operational costs and this is already being applied to the capture process at some operations, for example, by targeting higher surface to volume ratios for gas-liquid contactors and improved heat exchange geometries. Another potential application for additive manufacturing in CCS would be the improved durability and efficiency in moving components such as compressors. The US DoE are currently working with additive manufacturing to produce complex heat exchangers that are essential for carbon capture, aiming to intensify the manufacture process.

6. Advanced materials

Subsurface wetting (nanoparticles allowing for increased CO_2 storage or improved EOR), which would mean increased storage capacity in CCS and increased revenue from EOR. Composite pipes could be more flexible, therefore preventing (or reducing) corrosion behaviour, and would be easier to transport. This would mean reduced installation and maintenance cost and more tolerance of impurities in the CO_2 stream.

Both nanomaterials and composite materials could have a wide range of applications specific to CCS in materials and process improvement, as well as for CO_2 utilisation. Nanoparticles could help with subsurface wetting for increased reservoir exploitation (so increased storage capacity for CCS) and composite pipes could replace or protect steel in pipelines, reducing (or preventing) corrosion, meaning reduced maintenance costs, higher tolerance of impurities or corrosive material in pipeline and reduced capital costs though ease of installation. Such composite pipes would combine two or more materials to improve functionality, for example carbon fibre and plastics, and could incorporate additive manufacturing by using fibre-reinforced plastic deposition.

The image below demonstrates the estimated technology readiness levels (TRL) for the applications of emerging and enabling technologies, as described in detail above.

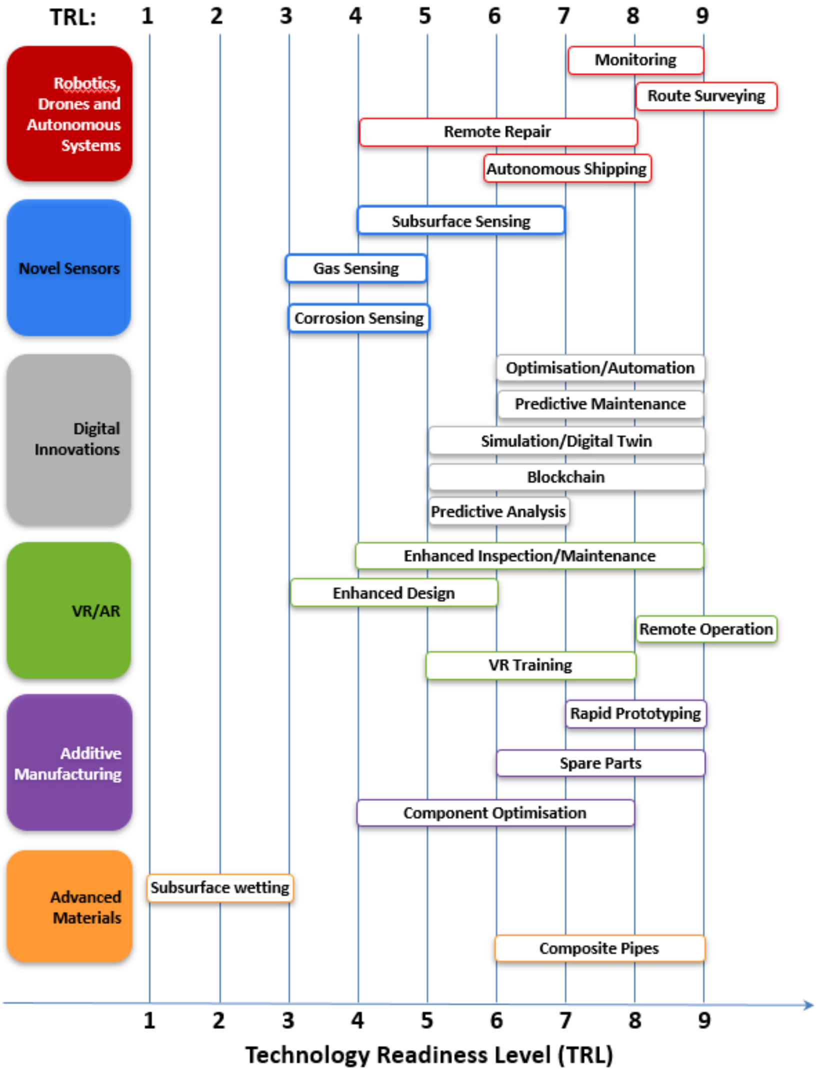

Figure 1. Estimated TRLs for emerging and enabling technologies *(figure 2-2, page 23, 'Value of emerging and enabling technologies for CCS', IEAGHG, July 2020)*

Costs of implementing digital & enabling technologies

The cost range of implementing emerging digital and enabling technologies is vast, but this report provides some illustrative examples. For robotics and drones, costs range from US $1,000-2,000 for simple equipment with cameras and up to $100,000's for highly advanced models. As component costs decrease the costs of the equipment are expected to decrease. Along with the upfront cost, implementing robotics and / or drones may require an operator meaning some labour cost. In sensor networks for leak reduction, equipment costs of around $32,600 /km have been estimated for sensors deployed along a pipeline; obviously this cost is dependent on the type, number and configuration of sensors. For machine learning, development costs on the order of $100,000's[1] can be expected and with additive manufacturing, capital costs for installing a 3D printer range from $21,000 to $7.1million. This is dependent on the deposition process and material, with costs varying with complexity and resolution;

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[1] Figure converted to USD using exchange rates of 21st May 2020, www.xe.com

however it is possible to use an additive manufacturing organisation, which offers printing of parts without the upfront capital cost of buying a 3D printer.

It must be noted that in addition to the upfront costs of the technology as described above, digital technologies require large amounts of data processing and storage capabilities, with the potential of these additional costs reaching $1million for very large datasets.

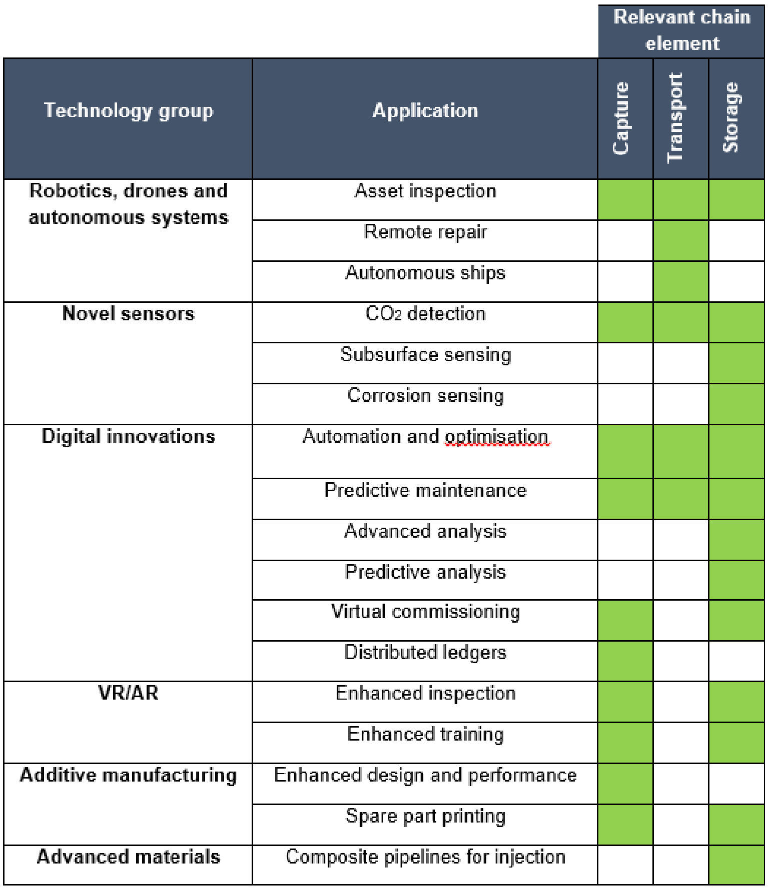
Risks & challenges of implementing digital & enabling technologies

The key risks for the digitalisation of processes can include digital failure (which could shut down a CCS network), system security breaches, data speed or connectivity (these technologies rely on data exchange), accountability (all stakeholders need to be able to trust the processes and decisions made by the technology), system integration (so the design of whole-system solutions would be beneficial to all for easy integration) and employment impacts (from the associated risks of job losses, although there is the potential to create new jobs and help upskill a workforce).

Other barriers to deployment or uptake of these technologies are industry acceptance, standardisation, skill shortage and unproven materials leading to technical uncertainty.

Potential impact of emerging & enabling technologies on CCS

The report assesses the potential impact of emerging technologies on CCS projects in terms of the quantitative impact on costs and also the qualitative impact on risks and challenges. Each part of the CCS chain (capture, transport and storage) was considered and the categories of technology applications were considered (as summarised in the table below) in the cost modelling.



		Relevant chain element		
Technology group	Application	Capture	Transport	Storage
Robotics, drones and autonomous systems	Asset inspection	🟩	🟩	🟩
	Remote repair		🟩	
	Autonomous ships		🟩	
Novel sensors	CO_2 detection	🟩	🟩	🟩
	Subsurface sensing			🟩
	Corrosion sensing			🟩
Digital innovations	Automation and optimisation	🟩	🟩	🟩
	Predictive maintenance	🟩	🟩	🟩
	Advanced analysis			🟩
	Predictive analysis			🟩
	Virtual commissioning	🟩		🟩
	Distributed ledgers	🟩		
VR/AR	Enhanced inspection	🟩		🟩
	Enhanced training	🟩		🟩
Additive manufacturing	Enhanced design and performance	🟩		
	Spare part printing	🟩		🟩
Advanced materials	Composite pipelines for injection			🟩

Figure 2. Summary of emerging technology applications across the CCS chain *(table 3-1, page 27, 'Value of emerging and enabling technologies for CCS', IEAGHG, July 2020)*

To model the costs, the values were first defined for CCS archetypes based on literature figures, then broken down into relevant components affected by digital and enabling technologies. The potential impact of each technology was estimated and the potential percentage cost reduction then applied to each component. More detail on the counterfactual costs and detailed cost components that were defined and taken into consideration, based on literature data, can be found in the report. In terms of the assumptions made for the cost modelling, the relevant cost components were already included in the counterfactual cost from the data source and, in addition where appropriate, assumptions were made for the CAPEX and OPEX components of capture, pipelines, ship transport and storage. It should be noted that cost reductions were defined for three project operational start dates to account for progression in technology development: 2025 (FOAK (first of a kind) projects either already undergoing or having recently completed FEED (front-end engineering design) and entering the construction stage); 2030 (NOAK (nth of a kind) projects, starting FEED within the next 2-5 years); and 2040 (NOAK projects starting FEED within the next 15 years).

Projected cost reductions in capture

The total lifetime project costs in capture plants are dominated by the technology therefore because the majority of digital and enabling technology applications target OPEX costs the expected overall impact of emerging technologies is small compared to the projected counterfactual cost reductions on going from FOAK (first generation amines) to NOAK (best available technology). Plants beginning in 2025 will have few enabling technologies available and so only small reductions in project costs are expected, 1-5% equivalent to \$1/tCO_2. This rises to 7-15% in 2030 and 9-20% in 2040. In all cases, the lowest absolute cost savings (but highest percentage cost reductions) are for plants that generate a purified CO_2 stream and the highest absolute savings are for post combustion plants with dilute CO_2 streams. Cement plants see the highest absolute cost savings.

In 2025, the largest contribution to cost reductions in CAPEX is due to using additive manufacturing for spare parts. In 2030, both additive manufacturing and digital innovations reduce CAPEX with a 1.2-1.5% reduction each. By 2040, digital innovations have by far the largest impact in plant operational costs and downtime, primarily associated with predictive maintenance.

Projected cost reductions in transport

Pipeline costs are dominated by CAPEX, therefore as in the capture section of the CCS chain, only modest reductions in project costs are expected. By 2025, overall cost reductions of less than 1% are estimated which rises to 4% in 2040. However, reductions in OPEX of 45% for onshore pipelines and 36% for offshore can be expected in the 2040 scenario due to the reduced supply chain losses, with the primary technologies driving overall cost reductions from novel sensors and robotics.

With ship transport, autonomous vehicles would dominate the potential cost reductions here, but savings in operational costs are outweighed by the increase in ship CAPEX, meaning an estimated decrease of only around 1%.

Projected cost reductions in storage

CO_2 storage sites show the most significant potential cost reductions. For sites operating in 2025, overall reductions of 2% in lifetime costs can be expected for onshore and offshore sites, resulting from 8-9% less OPEX costs and a reduction of 10% in supply chain losses. By 2040, 19% overall cost reductions are projected in offshore projects and 26% in onshore; a result of a 7-9% CAPEX reduction, 50% OPEX reduction and 50% reduction in injection facility downtime. For an offshore saline aquifer example, these reductions could equate to a saving of over \$45million in CAPEX and up to \$60million in OPEX. Shell have already identified cost reduction measures based on their experience at Quest.

Digital innovations will have the greatest impact on CAPEX, OPEX and downtime costs of a storage operation, mainly through automation and predictive maintenance. Site appraisal is another application that would benefit, with an expected reduction of 23% in site appraisal costs in 2040 due to a 40% decrease in seismic appraisal costs and 15% saving in well drilling appraisal. Additive manufacturing could contribute a saving through composite pipelines, both in CAPEX and OPEX.

Relative impacts of technologies

To compare the relative impacts throughout the supply-chain, levelised cost savings for a cement plant, offshore pipeline and offshore saline aquifer were considered in 2040. Across these examples, a combined saving of \$11/tCO_2 is projected. Of this, 56% is in base CAPEX or OPEX in capture and storage, rather than in downtime and leakage. Automation and predictive maintenance affect all cost components considered with the largest saving in capture plant maintenance OPEX (aside from downtime).

Robotics, drones and autonomous systems deliver benefits across the whole chain, but primarily impacting downtime and leakage due to improved monitoring and maintenance. The largest cost reduction from novel sensors is in storage appraisal costs along with reducing leakage and downtime. Additive manufacturing will have the greatest impact in capture downtime, VR and AR will primarily impact with reduced downtime and advanced materials are considered most applicable in storage projects. The figure below illustrates the magnitude of cost reductions due to emerging and enabling technologies in the three example sections of the chain, noting that the values are quoted to one decimal place to highlight the relative scale and are not a statement of cost certainty.

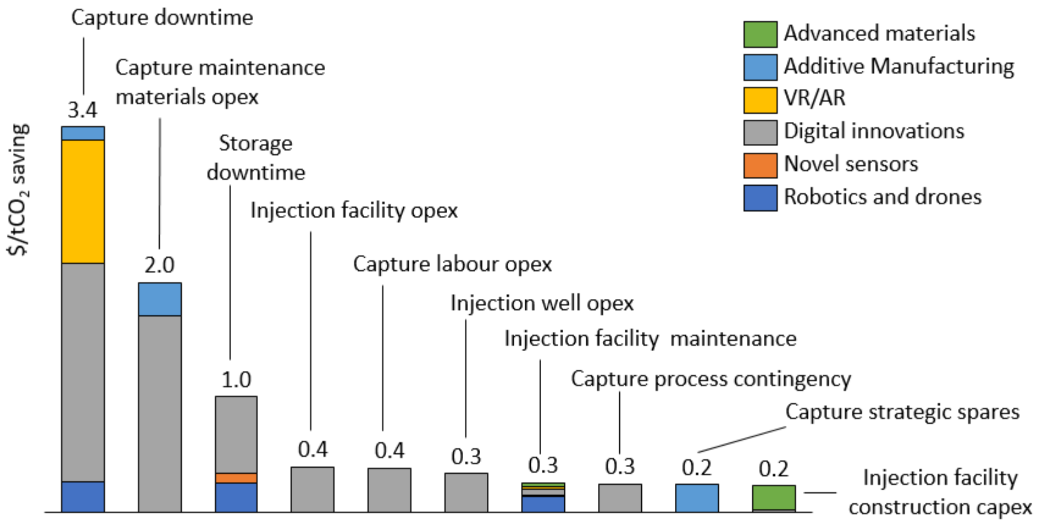


Figure 3. Comparison of magnitude of cost reductions due to emerging technologies across the CCS chain, based on capture from a cement plant, 180km offshore pipeline and storage in an offshore saline aquifer (all operating in 2040) *(figure 3-9, page 36, 'Value of emerging and enabling technologies for CCS', IEAGHG, July 2020)*

The report recognises that there are significant uncertainties in all estimations of cost reductions due to currently immature technologies, incomparable applications and lack of extensive quantitative data for CCS projects. Cost estimations related to additive manufacturing are particularly uncertain as they are highly site specific. Estimates for composite pipelines are currently imprecise due to the limited data on the allocation of injection facility costs. The largest impacts on costs recognised are from automation and predictive maintenance, but the degree to which processes may already be automated varies across projects, so the scale to which costs can be reduced will vary across projects. The impact of predictive maintenance also depends on the current maintenance strategy of specific projects. Sensitivities were run to illustrate the impact of uncertainties in selected cost reductions, which showed that the levelised lifetime costs of capture plants were most sensitive to variations in predictive maintenance assumptions (due to the large proportion of costs associated with downtime) and in storage sites, costs are equally sensitive to assumptions on automation and predictive maintenance (with a variation of ±2 percentage points in estimated cost reductions). The figure below illustrates the effect of variation in cost reduction potential of selected technology applications, using examples of a cement plant and offshore saline aquifer, both operating in 2040.

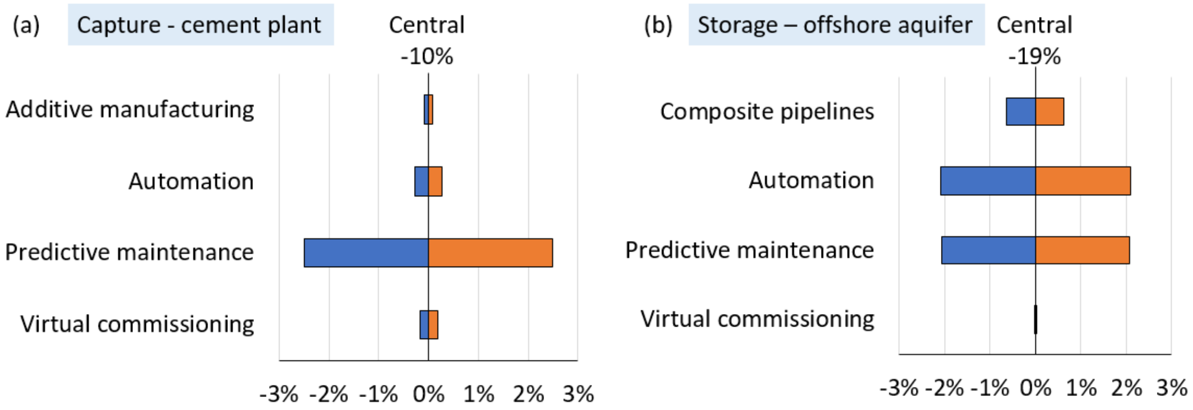
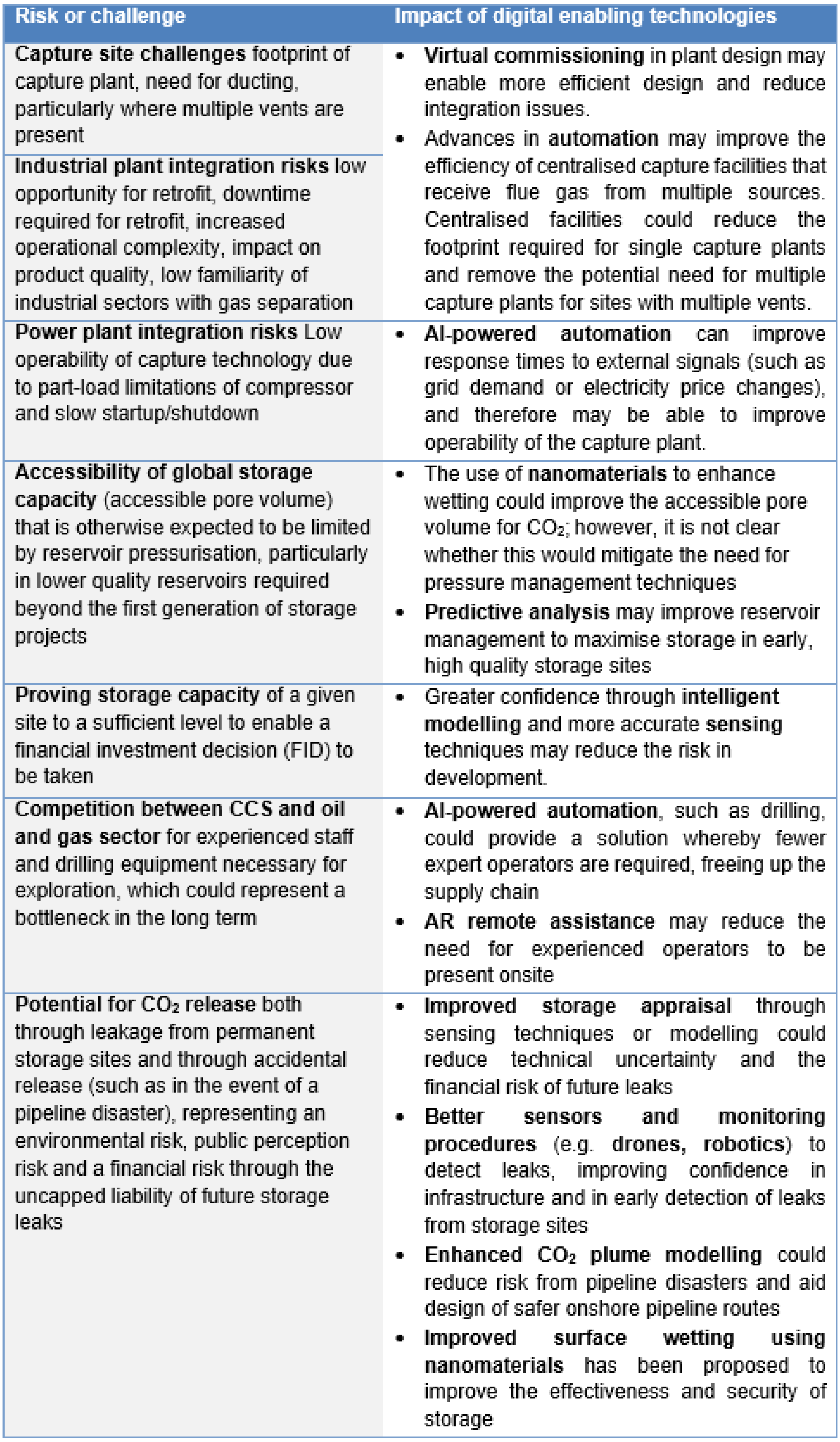


Figure 4. Effect of variation (±50%) in cost reduction potential (%) of selected digital and enabling technology applications on the overall reduction in lifetime cost of (a) a cement plant and (b) an offshore saline aquifer *(figure 3-11, page 38, 'Value of emerging and enabling technologies for CCS', IEAGHG, July 2020)*

Impacts of emerging & enabling technologies on risks & challenges of CCS

Challenges to large scale deployment include technical uncertainty of storage site performance, cross-chain coordination, plant integration challenges and the lack of a market for stored carbon. The main risks in CCS addressed are likely to be related to technical viability, although some political and financial barriers could be addressed through emerging technologies that increase confidence in CCS. Challenges in the coordination of CCS projects is a major barrier to full chain projects; a challenge that could be impacted by digitalisation. The table below summarises the potential impacts of emerging technologies on the risks and challenges associated with CCS.



Risk or challenge	Impact of digital enabling technologies
Capture site challenges footprint of capture plant, need for ducting, particularly where multiple vents are present	• **Virtual commissioning** in plant design may enable more efficient design and reduce integration issues. • Advances in **automation** may improve the efficiency of centralised capture facilities that receive flue gas from multiple sources. Centralised facilities could reduce the footprint required for single capture plants and remove the potential need for multiple capture plants for sites with multiple vents.
Industrial plant integration risks low opportunity for retrofit, downtime required for retrofit, increased operational complexity, impact on product quality, low familiarity of industrial sectors with gas separation	
Power plant integration risks Low operability of capture technology due to part-load limitations of compressor and slow startup/shutdown	• **AI-powered automation** can improve response times to external signals (such as grid demand or electricity price changes), and therefore may be able to improve operability of the capture plant.
Accessibility of global storage capacity (accessible pore volume) that is otherwise expected to be limited by reservoir pressurisation, particularly in lower quality reservoirs required beyond the first generation of storage projects	• The use of **nanomaterials** to enhance wetting could improve the accessible pore volume for CO_2; however, it is not clear whether this would mitigate the need for pressure management techniques • **Predictive analysis** may improve reservoir management to maximise storage in early, high quality storage sites
Proving storage capacity of a given site to a sufficient level to enable a financial investment decision (FID) to be taken	• Greater confidence through **intelligent modelling** and more accurate **sensing** techniques may reduce the risk in development.
Competition between CCS and oil and gas sector for experienced staff and drilling equipment necessary for exploration, which could represent a bottleneck in the long term	• **AI-powered automation**, such as drilling, could provide a solution whereby fewer expert operators are required, freeing up the supply chain • **AR remote assistance** may reduce the need for experienced operators to be present onsite
Potential for CO_2 release both through leakage from permanent storage sites and through accidental release (such as in the event of a pipeline disaster), representing an environmental risk, public perception risk and a financial risk through the uncapped liability of future storage leaks	• **Improved storage appraisal** through sensing techniques or modelling could reduce technical uncertainty and the financial risk of future leaks • **Better sensors and monitoring procedures** (e.g. **drones, robotics**) to detect leaks, improving confidence in infrastructure and in early detection of leaks from storage sites • **Enhanced CO_2 plume modelling** could reduce risk from pipeline disasters and aid design of safer onshore pipeline routes • **Improved surface wetting using nanomaterials** has been proposed to improve the effectiveness and security of storage

Figure 5. Summary of the potential impacts of emerging technologies on risks and challenges *(table 3-5, page 40, 'Value of emerging and enabling technologies for CCS', IEAGHG, July 2020)*

Implications of emerging technologies for global CCS deployment

Following the deployment trajectory assumed in the IEA 2°C scenario, total cumulative global savings of close to $200billion (10%) in lifetime costs of projects deployed up to and including 2040 could be achieved. Of this, 8% would be saved in CAPEX, 27% estimated to be saved in OPEX, 47% saved due to carbon costs of downtime and leakage and 13% savings are estimated in transport and storage (of which 96% is saved in storage projects). For capture plants, the power CCS sector accounts for the largest savings and the industrial sector accounts for 20% of savings.

Over half of the projected cost savings are due to digital innovations and their applications. Additive manufacturing accounts for half the savings in CAPEX, and 9% of overall savings. Most of the savings from drones, robotics, automated systems and novel sensors would occur in transport and storage. Figure 6 shows the distribution of the global cost savings by emerging technology group.

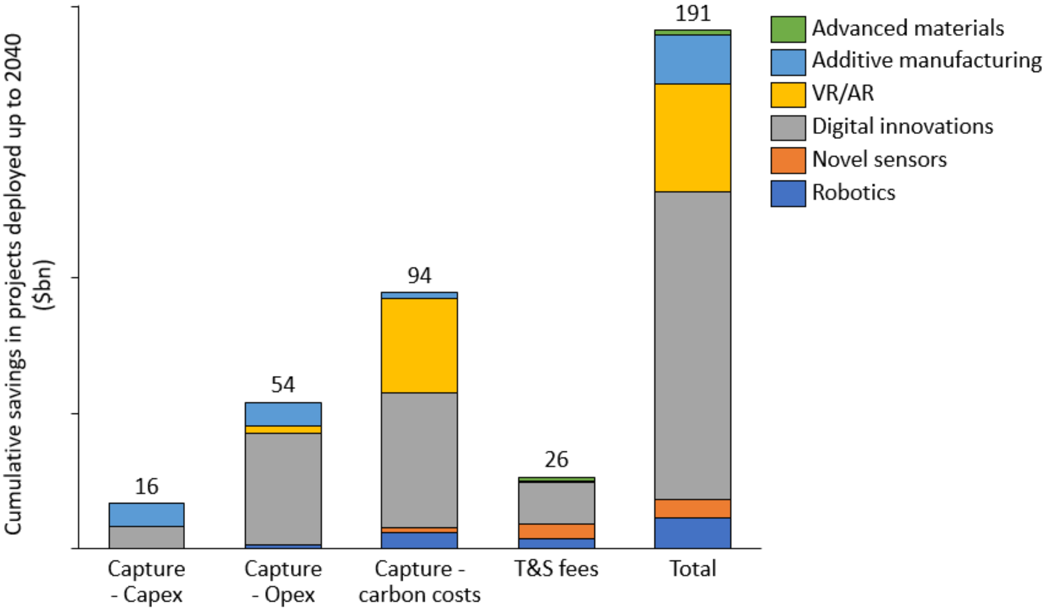


Figure 6. Distribution of global cost savings by emerging technology group *(figure 4-4, page 45, 'Value of emerging and enabling technologies for CCS', IEAGHG, July 2020)*

Conclusions

This report provides a high-level assessment of the potential impacts of digitalisation on CCS costs and risks and the implications of these impacts for global deployment, demonstrating that there are a wide range of relevant applications for emerging and enabling technologies in CCS that could potentially reduce costs and address risks and challenges. Although only some applications are currently under development in CCS, the benefits of these technologies discussed in the report are largely transferable from related sectors.

Significant savings are only expected to be realised from 2030, in line with the current technology maturity and development timescales of CCS, with AI and IoT in predictive maintenance and automation delivering the greatest potential reductions in cost. The greatest savings absolute (in terms of $ /tCO_2) are predicted to be in capture, whereas the greatest relative (percentage) savings are in storage. Cumulative savings of almost $200billion are possible through to 2040, which is a saving of 10% of the counterfactual investment cost.

Risks and challenges in CCS are most likely to be addressed through improved efficiency of integration, improved operational flexibility and reduced technical uncertainty. This will lead to better confidence for project developers, policymakers, regulators and financers to help facilitate global deployment.

Expert Review

The general consensus of the six expert reviews received were that the economic analysis was a useful piece of work and the study overall would be an important resource in broadening the outlook of the CCS community, providing touchpoints for the CCS sector to engage with more dynamic sectors of the economy.

Following the expert review, the contractors added more case-specific information on certain technologies, but noted that in some cases (i.e. advanced materials and drones) there were challenges due to the lack of publicly available information. More detail was also added on remote sensors, membranes and on uncertainties in the cost modelling section. Interest generated by the study on risks, timescales and a full sensing survey recommended an updated costs analysis, but this was beyond the scope of this study. It has been proposed for future work.

Recommendations

This report presents a high level assessment of the potential benefits based on the best available data, but there is significant uncertainty inherent in the cost reduction predictions. The scale of the projected cost reductions and relative impact of each technologies are likely to be similar to what can be achieved, the absolute savings (\$ /tCO_2) are uncertain. Suggestions of further work from IEAGHG include:

- Further work looking at the cost / benefit analysis for each of the emerging and enabling technologies,
- To monitor the next generation of CCUS projects to see how they deploy digital technologies and if appropriate, advise on the use of these technologies,
    - Following this initiative, it may be useful to undertake a specific exercise detailing how technologies have improved cost reduction and overall performance in CCS in 3, 5 and 10 years depending on how quickly the next generation of CCUS projects move forward.
- Future work to look not only at the operation but also the benefits offered by technology in the concept, design, FEED and EPC (engineering, procurement and construction) phases. The cascade of benefits through the entire lifecycle should then be assessed.

The contractors recommend further work including a more detailed assessment of the likely impact of integrating digital and enabling technologies into real CCS projects. This foundation would provide a broader in-depth assessment of the potential applications of each technology group within CCS, to enable more confident assessment of the level of impact expected.

In terms of assessing the wider implications of digital and enabling technologies, the report recommends that the following further work be undertaken:

- An assessment of regional factors affecting global uptake and impacts.
- An assessment of digitalisation of CCS within the context of the wider energy sector.

Once further evidence has been gathered, long-term future work could include activities such as:

- Defining a detailed roadmap for the development of digital technologies in CCS.
- Identification of incentives or targeted funding requirements for acceleration of digital technology uptake.
- Encouraging collaboration between key stakeholders to ensure uptake.

element energy

Value of emerging and enabling technologies in reducing costs, risks and timescales for CCS

Final report

for

IEAGHG

8th December 2019

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About the Authors

Element Energy is a leading low carbon energy consultancy working in a range of sectors including carbon capture and storage, low carbon transport, low carbon buildings, renewable power generation, energy networks, and energy storage. Element Energy works with a broad range of private and public sector clients to address challenges across the low carbon energy sector, and provides insight and analysis across all parts of the CCS chain.

Disclaimer

While the authors consider that the data and opinions contained in this report are sound, all parties must rely upon their own skill and judgement when using it. The authors do not make any representation or warranty, expressed or implied, as to the accuracy or completeness of the report. The authors assume no liability for any loss or damage arising from decisions made based on this report. The views and judgements expressed here are the opinions of the authors and do not reflect those of IEAGHG or any of the stakeholders consulted during this project.

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Executive Summary

Overview

Carbon capture and storage (CCS) is a proven technology in reducing greenhouse gas emissions and is recognised as a key part of the technology mix required to achieve global emissions targets. Despite this, deployment of CCS currently falls significantly short of the projected capacity that needs to be in service to meet these targets. Accelerating the rate of future development of CCS requires both political strategies and technological advances to support cost-effective deployment and operation.

A range of digital and enabling technologies are already helping the energy sector, as well as others, to reduce costs, risks and timescales for projects. The pace of development and adoption of these technologies is growing rapidly, and digitalisation is expected to deliver significant improvements in energy systems in the coming years. Many of the applications of digital technologies are expected to be transferable to CCS but the implications of these technologies for CCS have not previously been fully investigated or quantified.

Element Energy were commissioned by IEAGHG to carry out a horizon scanning exercise with the aim of understanding the relevance of digital and enabling technologies for CCS and assessing the benefits that they could offer to large-scale CCS deployment.

Relevance of digital and enabling technologies for CCS

A wide range of emerging and enabling technologies were considered, which have been broadly grouped into six categories according to their common features and applications:

1. **Robotics, drones and autonomous systems** includes all independent (physical) systems that are used to carry out specific tasks, either with significant operator input (near-term applications) or autonomously (future developments).
2. **Novel sensors** include improvements to existing sensing techniques, novel applications of sensor networks and novel sensing techniques.
3. **Digital innovations** include digital platforms and techniques for advanced data processing, communication and analysis. Specifically, this includes Internet of Things, Artificial Intelligence, simulation techniques, and blockchain.
4. **Virtual reality and augmented reality (VR/AR)** include immersive technology which either creates a virtual environment for the user to interact with (VR) or overlays virtual objects onto the real-world environment (AR).
5. **Additive manufacturing** is a suite of technologies that build up 3D objects via layer-by-layer deposition using computer-aided design (CAD), also referred to as 3D printing.
6. **Advanced materials** includes two specific areas of materials advancement: nanomaterials and composites.

Digital and enabling technologies offer a range of benefits to projects, including improved process efficiency, improved decision-making, and improved durability of components. Many of the applications and associated benefits of these technologies for CCS are likely to be similar in nature to those experienced in the energy and oil and gas sectors. In addition, several applications of digital and enabling technologies are already being developed for CCS, specifically including: subsurface sensing techniques, robotics and environmental sensing for storage site monitoring, machine learning for materials discovery, and additive manufacturing of capture technology components.

The relevant applications of digital and enabling technologies for CCS are summarised in Table 1.

Table 1 Applications of digital and enabling technologies for CCS and their benefits

	Application	Benefit
Robotics and drones	**Asset monitoring** – using robots/drones to monitor and inspect hazardous or difficult to reach assets.	Reduced cost, improved safety and effectiveness of monitoring.
	Route surveying – appraising proposed routes for pipelines using drones.	Improved route appraisal, reduced time and cost.
	Remote Repair – robots/drones with additive manufacturing capabilities repairing equipment	Reduced man-hours, cost and downtime for repair.
	Autonomous Shipping – remote controlled or autonomous ships	Reduced operational costs, more efficient ship design.
Novel Sensors	**Subsurface sensing** – novel methods to appraise and monitor CO_2 storage locations	Reduced appraisal costs and storage monitoring costs
	Gas sensing – improved CO_2 sensors to detect gas leakage in ‘supply chain’	Reduced loss of CO_2, avoided CO_2 tax
	Corrosion sensing – novel methods for corrosion monitoring in plants	Lower inspection cost, reduced risk of failure
Digital Innovations	**Process optimisation and automation** – intelligent algorithms to optimise and automate plant operations	Reduced costs, increased efficiency, reduced downtime
	Predictive maintenance – improved strategies through IoT and AI for continuous data gathering and analysis	Cheaper and more effective maintenance, lower failure rate leads to reduced downtime
	Predictive analysis – machine/deep learning to improve materials/process development	Reduced development time and costs for materials and processes
	Simulation and virtual commissioning – digital twins to simulate operations of plant	Lower commissioning time/cost, improved plant operation
	Verification and smart contracts – distributed ledger or blockchain solutions for verification and supply chain management	Increased trust, reduced administrative costs
VR / AR	**Enhanced inspection/maintenance** – displaying sensor data when inspecting equipment and connecting technicians to remote experts	Reduced maintenance costs, reduced maintenance time and decreased downtime
	Enhanced design – VR and CAD allow designers and operators to improve plant design	Reduced cost/time for design and commissioning, improved design
	Remote operation – VR to help operate robots, performing complex tasks in harsh environments	Reduced labour costs, improved safety
	VR training – operators gain experience in simulated plant environment or emergency scenarios	Reduced training costs, increased training standards
Additive Manufacturing	**Rapid prototyping** – streamlined design stages through rapid manufacture and iteration	Reduced design time and cost of prototyping and initial testing
	Spare parts – printing spare parts on/off site rather than keeping large spare part inventories.	Lower sunk capital, reduced lead time, reduced plant downtime
	Component optimisation – improved design of complex components	Reduced maintenance/equipment cost, improved performance
Advanced Materials	**Subsurface wetting** – nanoparticles can allow increased CO_2 storage or improved EOR	Increased storage capacity for CCS, increased EOR revenue
	Composite pipes – flexible pipes, preventing or reducing corrosion behaviour and easier to transport.	Reduced installation + maintenance cost, tolerance of impurities in CO_2 stream

Impacts of digital and enabling technologies on costs of CCS

The benefits of digital and enabling technologies are projected to be realised gradually, with little cost savings accessible to projects beginning operation within the next 5 years (2025) but greater cost savings available from 2030 and out to 2040. This reflects both the current maturity level of the relevant technologies and the development timescales of CCS projects.

While a large proportion of CCS costs are capex costs, the majority of applications of digital and enabling technologies affect opex costs; therefore only modest savings in base project costs (capex, opex and fuel) are projected (4-6% for capture plants, 1-2% for pipelines and 7-9% for saline aquifers by 2040).

However, reflecting the value of the benefits offered by many of the digital and emerging technologies, more significant cost reductions across the chain are projected to be in cost components associated with facility downtime (due to planned or unplanned maintenance) and supply chain losses[1] of CO_2.[2]

Across the CCS chain, the largest absolute cost savings ($/t$CO_2$) are for capture plants, with the largest relative cost savings (%) for storage sites (Figure 1a).

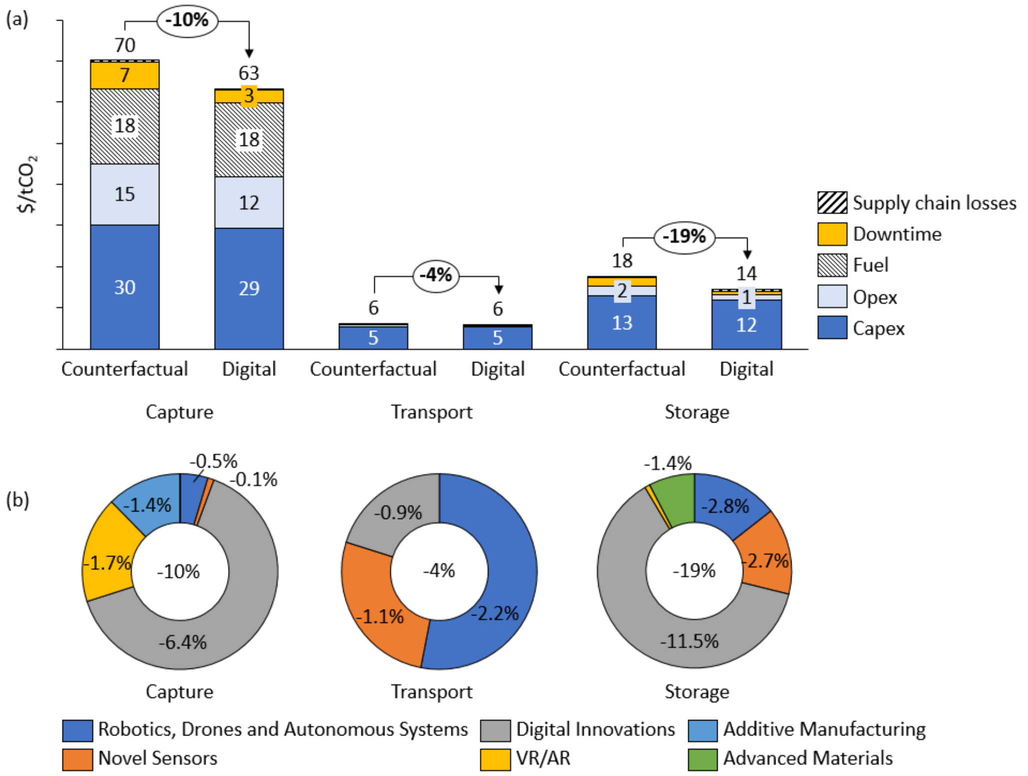

Figure 1 (a) Comparison of projected reductions in levelised lifetime costs across the CCS chain for projects starting operations in 2040; (b) Relative contribution of each technology group to the overall cost reductions for each chain element.

For capture plants, the lowest absolute cost savings but highest percentage cost reductions are expected for plants that generate a pure CO_2 stream (lowest counterfactual cost) and

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[1] Supply chain losses represent CO_2 leakage from infrastructure across the chain, analogous to losses within the natural gas sector; this cost is not intended to indicate any expectation of leakage from geological storage

[2] Both downtime and supply chain losses were represented as costs of emitted CO_2 by applying a carbon price in line with International Energy Agency projections.

the highest absolute savings are for post-combustion plants with dilute CO_2 streams. Cement plants experience the highest absolute cost savings.

Digital innovations contribute the largest cost reductions in both capture and storage. The greatest impacts resulting from novel sensors, and robotics, drones and autonomous systems are in transport and storage, whereas the largest cost reductions from VR/AR and additive manufacturing are in capture (Figure 1b).

Comparing projected cost reductions across the CCS chain, seven of the ten cost components that experience the largest levelised cost reductions ($/t$CO_2$) are either opex costs or costs of released carbon (downtime and leakage). Automation and predictive maintenance affect all of these cost components and, aside from reduced downtime, the largest saving is in capture plant maintenance opex.

Implications for Global Deployment

Following the deployment trajectory required to meet a 2°C scenario,[3] total cumulative global savings of close to $200bn (10%) in total lifetime costs of projects deployed up to and including 2040 can be possible (Figure 2). The majority of the projected savings are in the cost of capture plants. The largest savings are in the power CCS sector (Figure 3), accounting for 77% of the expected savings in capex, 76% of savings in opex and 61% of savings in costs of released carbon (downtime and supply chain losses).

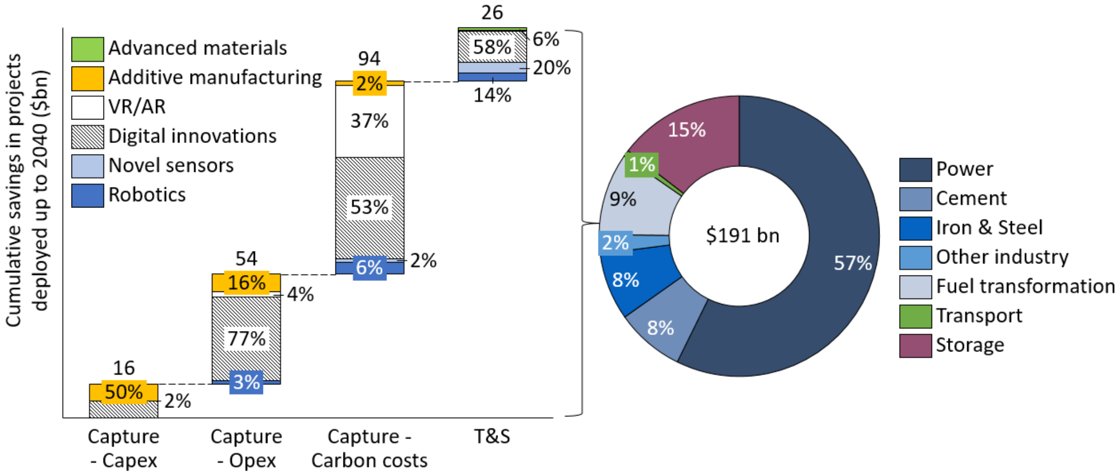

Figure 2 Projected cumulative global investment savings in CCS projects deployed up to and including 2040, following a 2°C scenario by cost element and technology group and by sector.

Impacts of digital and enabling technologies on risks, challenges and timescales of CCS

Aside from cost, a number of technical, political and economic challenges are limiting large-scale CCS deployment. The main risks of relevance to applications of digital technologies are expected to be related to technical viability, although some political and financial barriers may also be addressed through technologies that increase confidence in projects.

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[3] *Energy Technology Perspectives* (2017) International Energy Agency www.iea.org/etp2017

Capture site challenges and integration risks are expected to be reduced by digital innovations such as virtual commissioning to predict and eliminate issues prior to build and AI-powered automation to improve operability of power CCS plants.

A number of technological developments target uncertainty reduction, with particular relevance to storage site risks. Intelligent modelling and improved sensing techniques and procedures can improve confidence in prediction of storage site performance (injectivity and capacity) and improved confidence in CO_2 storage as a long-term solution through improved monitoring.

Challenges in **coordination of capture and storage projects** represent a major barrier to full chain CCS projects. However, while it is possible that this challenge may be impacted by digitalisation, the scale of the overall impact and the technology application(s) with the most potential impact in this area are unclear.

Based on current technology developments, timescales for global CCS deployment are not expected to be significantly reduced by digital and enabling technologies. Although some technologies can reduce lead times for components of project development, such as in design and materials supply, the overall impact on project timescales is likely to be fairly small. Developments in seismic analysis or other sensing technologies could potentially accelerate storage appraisal; however, there is currently no precedent for this within other sectors. However, it is possible that disruptive developments not foreseen here may become relevant in future.

Digital and enabling technologies are also subject to risks and challenges to their uptake and utilisation. For example, industry acceptance of new materials and processes can be a barrier to deployment, whereas widespread digitalisation of processes can introduce risks of data security. Given the benefits that these technologies can offer, the implications of these risks for deployment within CCS should be investigated further to identify measures to minimise their impact and facilitate uptake.

Recommendations for further work

Although this study has highlighted the technologies expected to bring strong benefits for CCS, additional research needs to be completed before the next steps in development of these technologies for CCS can be identified. Further work is recommended to address the significant uncertainty inherent in projections of cost reduction and the wider implications of digital technology uptake. Suggestions for further study include:

- **More detailed assessment of the likely impact of integrating digital and enabling technologies into real CCS projects**.
- **More in-depth assessment and modelling of the potential applications of each technology group within CCS** to enable more confident assessment of the level of impact expected.
- **Assessment of regional factors affecting global uptake and impacts.**
- **Assessment of digitalisation of CCS within the context of the wider energy sector.**

Once further evidence has been gathered, **a detailed roadmap** for the development of digital technologies in CCS can be defined, allowing **targeted funding** requirements for acceleration of digital technology uptake to be identified.

Contents

Glossary

AI	Artificial Intelligence
AM	Additive Manufacturing
AR	Augmented Reality
CAD	Computer Aided Design
Capex	Capital Expenditure
CCS	Carbon capture and storage (of CO_2)
CCUS	Carbon capture, utilisation and storage (of CO_2)
CO_2	Carbon dioxide
EOR	Enhanced Oil Recovery
FEED	Front End Engineering Design
FID	Final Investment Decision
FOAK	First of a kind
GPS	Global Positioning System
$GtCO_2$	Gigatonnes CO_2 (Billion tonnes)
HSE	Health, Safety and Environment
ICC	Industrial Carbon Capture
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IoT	Internet of Things
MMV	Monitoring, Measurement and Verification
$MtCO_2$	Megatonnes CO_2 (Million tonnes)
Mtpa	Megatonnes per annum (per year)
NGCC	Natural Gas Combined Cycle power plant
NOAK	Nth of a kind
Opex	Operational Expenditure
ROV	Remotely Operated Underwater Vehicle
T&S	Transport and Storage
TRL	Technology Readiness Level
VR	Virtual Reality

Note on Terminology

Whilst Carbon Capture, Utilisation, and Storage (CCUS) and Carbon Capture and Storage (CCS) are used almost interchangeably in the literature, for consistency purposes, this report only uses CCS, with exceptions when CCUS is used directly in the cited sources.

1 Introduction

1.1 Project context

Carbon capture and storage (CCS)

Carbon capture and storage (CCS) has been identified as a key technology that is essential for achieving global climate change targets.[4] As well as directly mitigating emissions from conventionally hard-to-decarbonise industries, CCS is an enabler of other renewable energy technologies, such as through decarbonisation of hydrogen production by steam methane reforming.

In order to meet global climate change targets, CCS needs to be implemented on a large scale, with up to 7 $GtCO_2$ projected to be stored annually by 2060 to achieve a 2°C scenario[5]. However, the high capital costs and risks associated with large-scale CCS have led to delays in supply chain development. As of 2019, only 18 large-scale CCS projects are in operation or under development, with the potential to capture a total of 33 $MtCO_2$ per year.[6] Accelerating the rate of future development of CCS requires strategies and technological advances to support cost-effective deployment and operation.

Current research and development into the reduction of costs, risks and timescales primarily focuses on conventional and established improvement processes or methods, such as searching for new solvents and sorbents to reduce the energy consumption for CO_2 capture, and developing shared CCS infrastructure. However, emerging digital and enabling technologies, such as artificial intelligence, robotics and additive manufacturing, have the potential to offer additional routes to cost and risk reduction.

The potential role of digital and enabling technologies in CCS development

Digital technologies have delivered benefits across the global economy for decades, including in the energy sector, but the pace of development and adoption of these technologies is growing rapidly.[7] With continued development, digitalisation is expected to deliver significant improvements in the safety, efficiency, flexibility and sustainability of energy systems in the coming years.

Many emerging digital and enabling technologies are already being used or developed to reduce costs, risks and timescales for the energy sector and infrastructure projects. There are many similarities between the sites and processes in CCS and those in industry, power generation, and oil and gas. As such, many of the applications and benefits of digital technologies within these sectors are likely to be transferable to CCS. However, the implications of these technologies for CCS have not previously been investigated or quantified.

1.2 Objectives

The primary objective of this study is to explore and identify which digital and enabling technologies might offer benefits for commercial-scale CCS deployment, including*:*

- Understanding current applications and key benefits of relevant technologies in related sectors

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[4] *The Global Status of CCS* (2018) Global CCS Institute
[5] *Energy Technology Perspectives* (2017) International Energy Agency
[6] *Transforming Industry through CCUS* (2019) International Energy Agency
[7] *Digitalization & Energy* (2017) International Energy Agency

- Understanding current maturity levels and expected development timelines of relevant emerging technologies
- Quantifying the potential impact of relevant technologies on current CCS cost projections
- Assessing the impact of these technologies on the risks and challenges associated with CCS implementation
- Assessing the likely global impact of these technologies in the context of projected deployment rates

1.3 Scope and approach

Scope

A wide range of emerging and enabling technologies were considered, which have been broadly grouped into six categories according to their common features and applications (Figure 1-1). Of these, five can be considered digital technologies since they utilise improvements in software and digital platforms. The final category (Advanced Materials) focuses on two important classes of materials development.

The analysis focused on the benefits of technologies arising from their direct inclusion in CCS projects. Although some cost reductions may indirectly be experienced by CCS project developers through implementation of these technologies in the mining, general manufacturing or construction industries, these aspects are considered to be outside the scope of this project. Other than these general applications, all applications of relevance to the costs and risks of implementation and operation of CCS projects were included in the analysis.

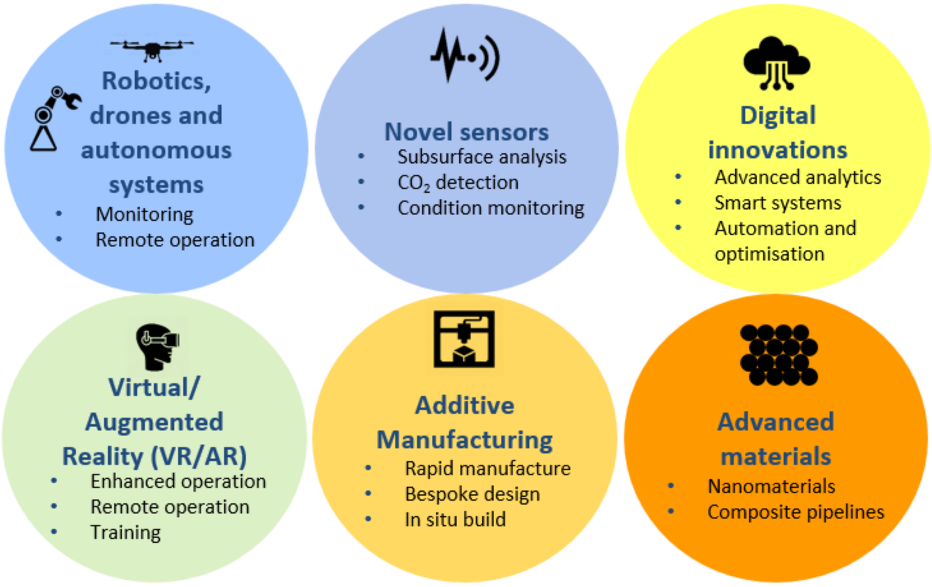

Figure 1-1 Digital and enabling technology groups considered in the review. Technologies are grouped by common features and applications.

Study Approach

The study approach is outlined in Figure 1-2 and is summarised below.

A horizon scanning exercise, comprised of an extensive literature review and digital technology stakeholder interviews, was conducted to determine the applications and potential benefits of digital and enabling technologies in industries similar to CCS.

The evidence from the horizon scanning was then used to inform an assessment of the relevance and potential impact of emerging technologies on CCS. By analysing the current processes and challenges within CCS, relevant applications of technologies across the components of the CCS chain were defined and their quantitative impact on project costs over time were modelled. The qualitative impacts on risks and challenges were also assessed, and the estimates and results were tested through engagement with external experts.

The implications of the identified cost and risk reductions were then explored within the context of the expected investment required to deploy CCS on the scale necessary for achieving global CO_2 climate goals. The results of the analysis have then been used to identify valuable areas of further work on the impacts of digital and emerging technologies.

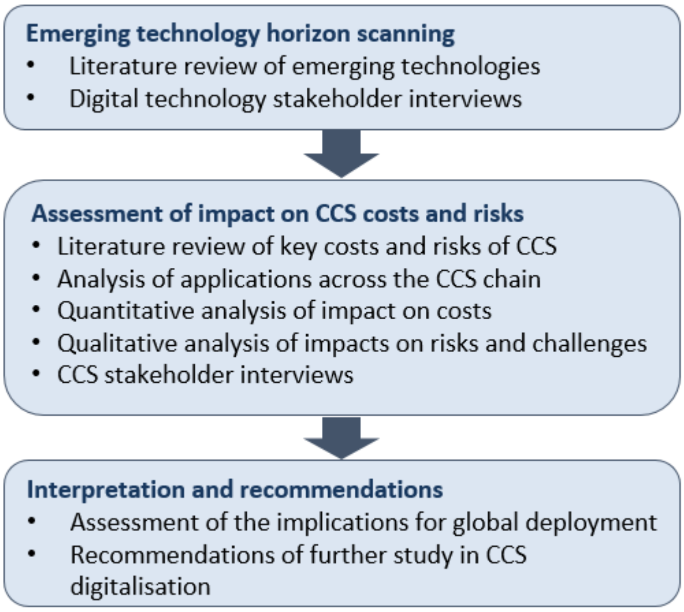

Figure 1-2 Summary of the study approach

2 Emerging and enabling technologies in related sectors

2.1 Introduction

A wide range of relevant emerging digital and enabling technologies were identified from the horizon scanning exercise which have been broadly divided into six categories according to common features and applications:

1. **Robotics, drones and autonomous systems** includes all independent (physical) systems that are used to carry out specific tasks. For the purposes of this study, autonomous systems are considered an advanced development of robotics, capable of reacting to changes in the environment without human intervention.
2. **Novel sensors** include improvements to existing sensing techniques, novel applications of sensor networks and novel sensing techniques.
3. **Digital innovations** include digital platforms and techniques for advanced data processing, communication, analysis and prediction. Specifically, this includes Internet of Things, Artificial Intelligence, advanced simulation, and blockchain.
4. **Virtual reality and augmented reality (VR/AR)** include immersive technology which either creates a virtual environment for the user to interact with (VR) or overlays virtual objects onto the real-world environment (AR).
5. **Additive manufacturing** is a suite of technologies that build up 3D objects via layer-by-layer deposition using computer-aided design (CAD), also referred to as 3D printing.
6. **Advanced materials** include two specific areas of materials advancement: nanomaterials and composites.

In practice, the technologies and the developments that underpin them are highly interrelated. For example, developments in low cost, low power sensors are critical to the deployment of robotics and drones, and developments in artificial intelligence and deep learning are necessary for achieving truly autonomous systems.

The following sections summarise the main applications of these technologies and the benefits that they deliver.

2.2 Applications and benefits of emerging technologies

2.2.1 Robotics, drones and autonomous systems

Industrial robots have been used in manufacturing and other industries for many years to aid or replace human operators, firstly with simple, repetitive tasks and then with more complex tasks as the sophistication of the robotics improve. Similarly, drones have expanded from being the sole purview of the military to being commercial and personal items used for photography, recreation and industry, following a wave of popularity driven by cost reductions.

The main advantages of these technologies for the energy sector are their ability to operate remotely within spaces that were previously either inaccessible or not possible to access safely or cost-effectively, such as at height, underwater, or confined spaces. As a result, their key applications are in monitoring and surveillance. They can also provide a cost-effective way of covering large distances, allowing for continuous monitoring of large areas.

Future developments such as perching[8] (allowing drones to land on a structure), air-to-water robotic vehicles[9] and robot-enabled additive manufacturing will allow increased functionality for additional tasks.[10] Robot-enabled construction is a strong trend in robotics, with wide-ranging applications.

Since robots and drones can be fitted with a range of sensors, more detailed information can be collected more rapidly and accurately than with human operators. By digitising surveillance data, better data analysis and long-term learning about the behaviour of assets can be achieved.

While a degree of autonomy for drones and robots is currently possible (for example, navigation via GPS), significant human input is required for more complex tasks. The transition to fully autonomous systems is currently a highly active area of research which relies on developments in artificial intelligence, particularly in the fields of deep learning and image recognition as well as symbolic reasoning and explainability.[11] Within the transport sector, driverless vehicles are a key application of autonomous systems. Marine transportation does not experience the same legislative barriers to autonomous vehicles as land transport[12], therefore autonomous shipping is a rapidly advancing sector.

Relevant applications for CCS

Applications of robotics, drones and autonomous systems within CCS are expected to be similar in nature to those in the energy sector, primarily targeting monitoring and maintenance.

The use of Autonomous Underwater Vehicles (AUVs) for monitoring of storage sites is already under development in the Energy Technologies Institute (ETI) MMV project[13] (completed in 2017) and the STEMM-CCS project.[14] In each project, the envisaged role of the AUV is to patrol the storage site area, detecting and quantifying any release of CO_2 into the marine environment via a range of onboard physical and chemical sensors. In the European Union, monitoring of storage sites for leaks is a requirement of the CCS Directive; AUVs offer a potentially cost-effective means of complying with this requirement and contribute to increased confidence and reduced perceived risk of CO_2 storage.

The relevant applications and developments of robotics, drones and autonomous systems for CCS are summarised in Table 2-1.

Table 2-1 Summary of relevant applications of robotics, drones and autonomous systems and their key benefits

Application	Description	Key benefits
Asset inspection	Drones fitted with cameras and sensors have been used to collect visual and environmental data for a wide range of both onshore, offshore and subsea	• **Reduced cost** through reduced man-hours and removing the need for

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[8] Zhang, K. et al. (2018), Journal of Field Robotics
[9] Chen, K., et al., Science Robotics Vol. 2, Issue 11, 2017, doi: 10.1126/scirobotics.aao5619
[10] K. H. Petersen et al. Science Robotics Vol 4, Issue 8, 2019, doi: 10.1126/scirobotics.aau8479
[11] Symbolic reasoning is a form of automated reasoning within AI that works with human-readable representations of AI problems; Explainability aims to address the problem of AI-based decisions not being understandable by humans
[12] *Digitalization & Energy* (2017) International Energy Agency
[13] https://www.eti.co.uk/programmes/carbon-capture-storage/measurment-modelling-and-verrfication-of-co2-storage-mmv
[14] http://www.stemm-ccs.eu/

and monitoring	structures, including: oil and gas tankers (*see Case Study 1*), gas flare stacks,[15] boilers,[16] chimneys and subsea pipelines.[17] **Gas detection** is one area targeted by robots and drones. Drones fitted with gas sensors (including CO_2 sensors) are capable of detecting plumes during flight[18], and drones and robots are being trialled to detect methane gas leaks in refineries and gas fields.[19],[20] Marine autonomous systems are under development for routine subsea inspection and have been proposed for use in both visual inspection of decommissioned offshore oil and gas structures[21] and for monitoring of CO_2 release from long-term storage (see text for details).	specialised safety equipment • **Reduced downtime** as a result of faster, in-operation inspection • **Improved safety** through avoidance of working at height or in hazardous environments • **Lower risk** of failure through early detection of faults • **Better data** enabling learning and monitoring over time • **Access to previously inaccessible assets** such as narrow pipelines[22]
Route surveying	Drones have been used to carry out geometric mapping of construction sites, transport routes and pipeline routes,[23] collecting visual and landfall data that can be processed digitally to inform design.	• **Reduced time and cost** of appraisal of transport routes • **Improved data quality** from higher resolution data • **Improved safety** where surveying is required in hazardous terrain
Remote repair	Robots have been used to carry out routine maintenance of natural gas pipelines (*see Case Study 2*). Equipping robots and drones with additive manufacturing capabilities is a key area of current development, with relevant applications including remote pipeline	• **Reduced cost** through reduced man-hours and less disruptive repair • **Reduced downtime** as a result of faster, in-operation repair

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[15] https://thecyberhawk.com/case-study/shell-moerdijk-flare-inspection-netherlands/

[16] https://www.flyability.com/casestudies/elios-2-tested-15-times-by-ronik-inspectioneering-approved-as-a-formal-inspection-tool

[17] *The Efficiencies of Low Logistics Man-portable AUVs for Shallow Water Survey Operations* A. McMurtrie. Available at https://www.subseauk.com/documents/ncs%20survey.pdf

[18] http ://scentroid.com/scentroid dr1000

[19] http://www.robogasinspector.de/

[20] https://medium.com/the-fourth-wave/drone-mounted-sensors-sniff-out-leaks-on-gas-fields-e0e0ee284d73

[21] D. O. B. Jones *et al.*(2019) Science of the Total Environment doi: 10.1016/j.scitotenv.2019.02.310

[22] Mills GH et al., Robotics 2017. Available from: http://www.mdpi.com/2218-6581/6/4/36

[23] https://www.aboutpipelines.com/en/blog/how-pipeline-companies-are-using-drones-for-surveying-and-safety/

	repair and, ultimately, complex construction.	- **Extended lifetime** of components
Autonomous shipping	Remote controlled and autonomous ships are currently under development by Rolls-Royce and Yara, with the first voyage taking place in 2018.[24] These state-of-the-art ships draw on advances across enabling technologies, including AI, VR and sensing.	- **Reduced operational costs** due to removal of crew, optimised routing and conditional monitoring - **More efficient ship design** due to removal of crew support requirements

Case Study 1 - Shipping tanker inspection[25]

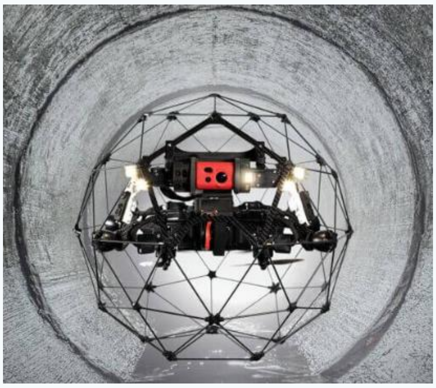

Image credit: Flyability (Flyability.com)

Sector: Maritime industry

Application: According to current class society rules, the tanks of ships must be inspected for corrosion and structural damage every 2.5 years. Traditional methods require a visual survey by teams of 3-4 qualified surveyors using ropes or scaffolding, as well as thickness measurements performed by a technician. These inspections are costly and slow, resulting in significant downtime, and put inspectors at risk due to working at height and in hot, confined spaces.

In 2018, engineering company Plimsoll used a drone operated remotely by a team of two from the ground to inspect 6 tanks and collect sufficient data to satisfy the class society requirements.

Key benefits: Reduced time, cost and risk; the inspection time was reduced from 18 days to 1 day, and the inspection cost was reduced from $21,600 to $2,500 (saving of 88%). Operating remotely removed the need for working at height in confined and potentially harmful conditions.

Relevance to CCS: Tanker inspection is a requirement for all cargo vessels and therefore is directly relevant to CO_2 shipping. However, drones have been used to inspect a wide range of assets in the energy sector and are therefore widely applicable for a range of maintenance and monitoring applications across the CCS chain.

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[24] https://www.digitaltrends.com/cool-tech/rolls-royce-ends-the-year-with-successful-test-of-an-autonomous-ferry/

[25] https://www.flyability.com/casestudies/shipping-inspections-smooth-sailing-with-drone-technology

Case Study 2 - Pipeline repair[26]

Sector: Gas network


Image credit: ULC Robotics

Application: In 2018, Cadent trialled CISBOT inspection robots to carry out maintenance work to gas pipes below Oxford Street and The Strand in London. Controlled remotely, the robots operate directly inside the pipe, injecting sealant into joints and extending their lifetime by decades. Traditional maintenance methods require teams of engineers, large-scale excavations and potential disruption to the gas supply. In comparison, the CISBOT solution only required one excavation site per 500m of pipe, and no disruption to supply.

Key benefits: Reduced time and disruption. The maintenance time was reduced from nine months to nine weeks. Removing the need for excavations and reduced the impact on the local area; carrying out the works while the pipe was in operation reduced disruption for customers.

Relevance to CCS: In-pipe, robotic inspection and maintenance is directly transferrable to CO_2 pipelines. With lower cost and less disruptive maintenance and inspection techniques available, the need for more expensive techniques such as pigging may be reduced, and the lifetime of pipelines may be extended.

2.2.2 Novel sensors

Sensors are applied in virtually every facet of society and underpin many future enabling technologies. Within industry, sensors are widely used to monitor process parameters such as flow, temperature and pressure. For the oil and gas sector, subsurface techniques to evaluate and monitor reservoir behaviour are crucial for developing and managing production sites.

Developments in sensing either target improved capabilities through increasing resolution, accuracy, sensitivity and novel measurement techniques; or increased usability by reducing cost, weight, size or power requirements. For subsurface sensing, conventional sensing techniques such as gradiomanometer surveys[27] or surface seismic surveys can be invasive and/or costly, and as such are typically carried out periodically. The development of wireless and/or in-well, low cost and more sensitive techniques can allow for more continuous monitoring, resulting in improved production and reducing costs due to more efficient installation, avoidance of invasive procedures and either avoided or more efficient work-overs (*see also Case Study 3 and Case Study 4*).[28] Significant cost reductions and opportunities for improved data collection can be afforded by sensors that can make use of natural or continuous sources of seismic energy (for example, in-well fibre-optic sensors[29] and surface seismic sensors, *see Case Study 3*).

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[26] *Network* October 2018, p. 25-29
[27] A pressure sensing technique for measuring the average density of the fluid at different depths in a completed production or injection well
[28] https://www.oilandgaseng.com/articles/wireless-monitoring-saves-hours-on-each-well-workover/
[29] https://www.tendeka.com/wp-content/uploads/The-advance-and-adoption-of-wireless-intelligent-completions.pdf

Wearable sensor technology in the form of 'Smart PPE' is an important area of development within hazardous industries such as offshore oil and gas. Such systems for integrated safety reporting and solutions can locate workers on a site and provide real time information of hazards[30]. Although CO_2 storage processes are similar to those in oil and gas drilling operations, the safety risks associated with handling CO_2 are in general considered to be much lower. The impact of wearable technologies that specifically target safety is therefore considered to be much lower for CCS.

Relevant applications for CCS

The main applications of novel sensors relevant to CCS are expected to be similar to those in the oil and gas industry, particularly in the areas of asset management (corrosion sensing), subsurface sensing and gas detection.

Geological storage of CO_2 requires many similar subsurface sensing techniques to those used in the oil and gas industry, and several techniques are already being trialled in current CO_2 storage projects. Shell's Quest CCS project is using a range of sensing techniques, including InSAR[31] satellite imaging, distributed temperature sensing, distributed acoustic sensors and downhole microseismic techniques for monitoring CO_2 storage and well integrity.[32] Distributed acoustic sensing is also being trialled in the CO2CRC Otway Stage 3 Project, aiming to provide on-demand, in-well seismic data for high-quality 4D imaging of the CO_2 plume migration and validation of pre-injection modelling of plume storage security.[33,34]

The detection of potential CO_2 releases through the CCS supply chain is also an area that is currently under investigation. For example, the STEM-CCS project and others[35] have developed a range of complementary techniques for sensing of CO_2 in the marine environment and on the seabed for detection of potential releases from offshore storage sites during ongoing monitoring. Future improvements in accuracy of aqueous sensing may be enabled by advances such as microfluidics.[36]

Low cost sensors have also been investigated for detection of CO_2 above transmission pipelines.[37] Improved leakage identification can reduce actual losses but also improve confidence among the public and stakeholders as to the security of transported and stored CO_2.

The applications and developments of relevance to CCS are summarised in Table 2-2.

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[30] https://www.corvexsafety.com/safety.html
[31] Synthetic Aperture Radar Interferometry
[32] Shell Quest Carbon Capture and Storage Project Measurement, Monitoring and Verification Plan (2017)
[33] https://silixa.com/wp-content/uploads/Case-Study-High-resolution-far-offset-VSP-survey-with-Carina-Sensing-System2.pdf
[34] http://www.co2crc.com.au/reducing-cost-carbon-storage/
[35] Innovate UK funded project, number 100814
[36] I. Perez de Vargas Sansalvador *et al.* (2018) Microchemical Journal vol. 139, p. 216-221
[37] *Final report of atmospheric monitoring of pipeline leakage* (2013) $CATO_2$

Table 2-2 Summary of relevant applications of novel sensors and their key benefits

Application	Description	Key benefits
Subsurface sensing	Subsurface sensing is necessary for appraisal of both oil and gas production sites and CO_2 storage sites, and for monitoring of wells during operation. Typical monitoring of wells requires repeated, periodic surveys that can be costly. Relevant developments targeting low cost, continuous and more accurate monitoring include wireless sensors (see *Case Study 3*),[38] microgravimetric sensors[39] and fibre-optic techniques[40] (see *Case Study 4*).	• **Reduced design costs** by replacing conventional sensors in well exploration/appraisal • **Reduced operational costs** through more accurate and more efficient monitoring
Gas sensing	The development and application of sensors for detecting low levels of gas release can improve early detection of leaks and low-level leaks, minimising gas release.	• **Reduced loss of gas** to the atmosphere • **Improved confidence in projects** through continuous monitoring
Corrosion sensing	Recent innovations have established novel methods for the non-destructive monitoring of corrosion in offshore steel structures, aimed at replacing labour intensive and limited conventional manual inspection.[41]	• **Reduced operational cost** of inspection • **Reduced risk** of asset failure through enabling predictive maintenance • **Higher data quality** than manual inspection

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[38] http://www.innoseis.com/
[39] https://www.silicong.com/reservoir.html
[40] https://silixa.com/solutions/environmental-and-infrastructure/co2-storage/vsp-and-surface-seismic/
[41] https://www.brunel.ac.uk/research/Projects/PileSense

Case Study 3 - Seismic sensing[38]

Image credit: Innoseis

Sector: Oil and gas

Application: Conventional onshore seismic sensing requires networks of sensors connected by cables to be distributed across an area which is labour intensive to deploy. Innoseis have developed alternative low power, wireless sensors that can be distributed twice as fast and can easily be scaled up to deliver data at much higher resolution than conventional sensors (one million node networks). Initially tested for gas extraction in Groningen, these sensors have been trialled by Shell since 2012.[42]

Future developments are targeting solar-powered sensors, to extend their lifetime in the field, and devices to detect low-level (natural) vibration, eliminating the need for externally-generated vibration sources (such as trucks).

Key benefits: Reduced costs and better data quality, leading to reduced uncertainty in seismic analysis. Labour costs of deploying the sensor networks can be reduced by 50% compared to conventional sensors.

Relevance to CCS: Seismic analysis is crucial in storage site appraisal as well as ongoing monitoring of sites during and after operation. Faster and easier deployment, better data quality and more continuous monitoring capabilities have significant opportunities for cost and risk reduction in CO_2 storage.

Case Study 4 - In-well monitoring[43]

Image credit: SmartFibres

Sector: Oil and gas

Application: Conventional management of fractured carbonate oil rim reservoirs involves repeated, manned well interventions carried out every 6-12 months. Well interventions are costly, bring health and safety risks and accuracy of the data has been questioned. Smart Fibres have trialled fibreoptic sensors as an alternative to track oil rim movement across a reservoir and to optimise control of oil production. The sensors are deployed directly in the well and provide continuous monitoring without the need for repeated well interventions. The sensors were commercialised in 2016 following 7 years of development and 5 years of trials.

Key benefits: Reduced operational cost, reduced health and safety risk and improved oil production rate. Continuous monitoring improves reservoir understanding and allows better decision-making regarding which wells to produce from and when.

Relevance for CCS: In-well sensors are already being trialled in CCS projects to monitor storage sites during operation for on-demand, high quality imaging of CO_2 plume migration.

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[42] https://oilprice.com/Energy/Energy-General/Shells-New-Sensors-Could-Reduce-Exploration-Costs-Dramatically.html

[43] https://www.smartfibres.com/files/pdf/DPS_Case_Study.pdf

2.2.3 Digital innovations

Within this study, digital innovations encompass novel software techniques and digital systems that enable increased productivity, enhanced connectivity, and optimised and automated processes.

These innovations include:

- **Internet of Things (IoT):** relates to the collection of continuous or near-continuous information from a network of devices. In the oil and gas industry, primary IoT-enabled business objectives are optimisation, reliability and new value creation.[44]

- **Artificial intelligence (AI) and machine learning:** AI systems employ algorithms to intelligently interpret data to make predictions and to generate appropriate responses. AI and machine learning are key enablers for autonomous systems, with development focused on applications for navigation and control.

- **Blockchain:** is a range of software products for distributed data storage and transfer. It aims to maintain an immutable record of digitally signed data entries that allow verification of transactions between parties that need guarantee of trust (distributed ledger); however, it should be noted that instances of hacking of blockchain records have been reported.[45] Cryptocurrencies are the most recognisable applications but a range of applications across industries have been proposed or developed. For the energy industry, transactions between ‘prosumers’[46] are a likely application.

IoT and AI are intricately linked since, as the volume and detail of data gathered around industrial sites by IoT sensors grows, there are increasing opportunities to use this large volume of data for intelligent analytics. A key benefit of new technologies is the ability to make full use this data to generate insights and improve decision making.[44] Predictive maintenance is a major application of AI which utilises continuous monitoring data to predict and prevent failure (*see Case Study 5*).

AI can also make use of historical datasets to predict behaviour of materials and resources, enabling rapid discovery of new materials or strategy development (*see Case Study 6*).

Automated processes to-date have aimed to replace humans in low-skilled, repetitive tasks; however, new applications such as AI-powered drilling[47] in the oil and gas sector are aiming to achieve a level of control that is on par with or better than experts.

Improved communication and coordination of actors within a system are additional benefits of these technologies. For example, in the power sector, IoT and AI developments promise greater flexibility of the electricity grid through smart demand side response and integration of decentralised power generation (including at-home devices).[12]

Relevant applications for CCS

Automation, optimisation and predictive analysis are applications that are highly transferable to CCS. The ability to collect data from multiple remote sensors and from multiple sources

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[44] *Connected barrels: Transforming oil and gas strategies with the Internet of Things* (2015) Deloitte Insights

[45] https://www.technologyreview.com/s/612974/once-hailed-as-unhackable-blockchains-are-now-getting-hacked/

[46] A person who produces and consumes, such as a homeowner that generates electricity with solar panels or that owns an electric car with vehicle-to-grid capabilities

[47] https://www.hartenergy.com/exclusives/potential-ai-powered-directional-drilling-31723

represents significant opportunities for monitoring, particularly for in-well and subsurface processes.

Capture processes are suitable for automation and processes across the CCS chain are already automated to some extent. A pilot plant at Imperial College London is currently trialling a scalable automation system for controlling all aspects of plant operation including data monitoring, engineering configuration, maintenance and safety routines.[48] Extension of this concept to an AI-driven, autonomous system is feasible.

Machine learning has also been applied to materials design for discovery of novel capture materials[49, 50]. Based on databases of known materials properties, intelligent deep learning algorithms have been shown to predict CO_2 adsorption properties of materials, allowing thousands of materials to be evaluated in a few hours rather than months. Such reductions in materials development have the potential to deliver high performance capture materials earlier than by traditional research and development techniques.

Blockchain-powered platforms for carbon trading are also under development[51] for tracking and verifying carbon removal and facilitating carbon removal certificate trading between carbon-generating businesses and soil sequestration projects. Although this application focuses on negative emissions solutions, it is feasible that a similar system may also be applied for geological storage.

The applications of digital technologies relevant to CCS are summarised in Table 2-3.

Table 2-3 Summary of relevant applications of digital innovations and their key benefits

Application	Description	Key benefits
Process optimisation and automation	Machine learning systems use intelligent algorithms to optimise operations in changing conditions. These algorithms can signal and rapidly react to change, improving process efficiency. These have been used in many fields, such as in the power sector to control fuel delivery,[52] reduce emissions,[53] rapidly respond to frequency changes in the electricity sector,[54] and automate drilling of shale wells.[47]	• **Reduced downtime** due to fluctuations in product/input quality • **Increased revenue** through maximised performance and improved accuracy of repetitive tasks • **Reduced labour costs** through replacing human workers • **Upskilled workforce** where repetitive tasks are replaced or **augmented expertise** where skilled tasks are automated

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[48] https://new.abb.com/control-systems/industry-specific-solutions/oil-gas-and-petrochemicals/system-800xa-for-pilot-plant-at-imperial-college-london
[49] https://phys.org/news/2018-09-machine-scientific-discoveries-faster.html
[50] Z. Zhang *et al. Angewandte Chemie* (2019) https://doi.org/10.1002/anie.201812363
[51] https://nori.com/
[52] Innovate UK funded project, number 102492
[53] https://new.abb.com/control-systems/industry-specific-solutions/oil-gas-and-petrochemicals/using-artificial-intelligence-to-reduce-environmental-impact
[54] Financial Times (2017)

Predictive maintenance	Using IoT and AI to continuously collect and analyse performance data, failure can be predicted with greater accuracy and maintenance of parts can be optimised to be carried out as and when required, rather than using preventative or reactive approaches. This approach has been implemented in a range of sectors including oil and gas[55] and manufacturing[56]	• **Reduced maintenance costs** by replacing components only when needed, and ahead of critical failure • **Reduced downtime** through reduced incidence of critical failure
Predictive analysis	In the oil and gas sector, predictive analysis based on historic production data has been used to optimise oil production from wells (*see Case Study 6*). In materials science, predictive analysis has been used to automate materials discovery and optimisation[57, 58] and to automate searches for new materials applications.[59]	• **Reduced development time and costs** for materials and processes
Simulation and virtual commissioning	Virtual replicas of planned or existing facilities can be used to simulate operations and the implementation of novel processes before replicating them in the real world.[60] By identifying technical issues in the virtual plant, construction and commissioning in the real world can be rapidly optimised at low risk.	• **Reduced commissioning time** using pre-identified optimal conditions • **Reduced commissioning costs** through less materials wastage and reduced man-hours • **Increased experience of staff** ahead of real-world commissioning
Verification and smart contracts	Blockchain solutions have been applied in a range of sectors for verification of compliance[61], supply chain management[62], and smart contracts[63], removing the need for third party verification and allowing task automation (*see Case Study 7*)	• **Increased trust** in verification of transactions • **Reduced administration costs** of issuing and verifying transactions

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[55] https://emerj.com/ai-sector-overviews/predictive-analytics-oil-gas-industry-current-applications/
[56] https://www.ibm.com/services/technology-support/multivendor-it/predictive-maintenance
[57] https://www.materialsproject.org/about
[58] https://www.sciencedirect.com/science/article/pii/S2352847817300618
[59] https://www.nature.com/articles/s41586-019-1335-8
[60] https://www.simsol.co.uk/scenarios/virtual-commissioning/
[61] https://www.openaccessgovernment.org/blockchain-technologies-automatic-regulation-compliance/41885/
[62] https://www.ibm.com/blockchain/industries/supply-chain
[63] https://blockgeeks.com/guides/smart-contracts/

Case Study 5 - Preventative maintenance[64]

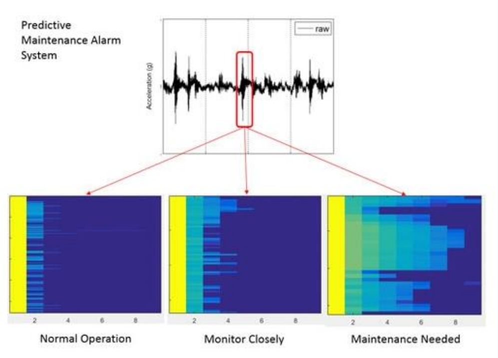

Image credit: Mathworks

Sector: Oil and gas

Application: At onshore oil and gas well sites, as many as 20 trucks may operate simultaneously with positive displacement pumps to inject water and sand mixtures into drilled wells. In the event of critical pump failure, spare trucks must be deployed to ensure continuous operation.

To reduce maintenance costs, engineers at Baker Hughes used machine learning to develop a pump health monitoring system that could predict pump failure. Temperature, pressure and vibration data collected from sensors on the trucks was used to determine which signals had the greatest influence on wear and tear, and this information was used to train a neural network to use relevant sensor data to predict failure in operational trucks. Maintenance strategies based on the algorithms' predictions ensured that parts were replaced on a not too soon, not too late basis.

Key benefits: Maintenance and replacement costs were reduced by 30-40%. Due to the reduced risk of critical failure, the number of additional trucks required on each site could be reduced, representing additional revenue of ~$10 million per truck.

Relevance for CCS: Predictive maintenance has wide-ranging applications across all parts of the CCS chain, replacing routine preventative maintenance for critical equipment.

Case Study 6 - Predictive analysis[65]

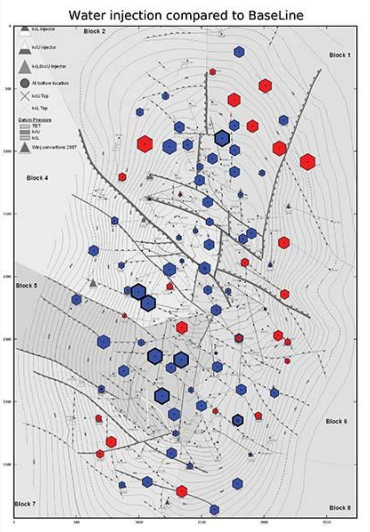

Image credit: FOROIL

Sector: Oil and gas

Application: FOROIL has developed a Digital Oil Recovery™ programme that uses historical production data to optimise recovery from brownfield sites. With 7-10 years of data from 15-20 wells, the software uses machine learning to analyse millions of development plans in a matter of hours and identify optimum future development. This system was applied in the San Francisco field to identify the optimum conversion and water injection plan, and the optimum sand-selective injection and production pattern.

Key benefits: Better reservoir management, resulting in ~1m additional barrels of oil (bbl) produced over previously forecast yield in two years.

Relevance to CCS: As more empirical storage site data is collected this type of analysis may enable better storage site management and/or better performance predictions of new sites.

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[64] https://www.mathworks.com/company/user_stories/baker-hughes-develops-predictive-maintenance-software-for-gas-and-oil-extraction-equipment-using-data-analytics-and-machine-learning.html

[65] http://www.foroil.com/dor-overview.php

Case Study 7 - Blockchain verification

Sector: Academic

Application: Gradbase is a platform for issuing and verifying academic qualifications using blockchain.[66] Conventionally, University qualifications are verified manually which in some cases can require three full-time staff to process requests.[67] Using Gradbase, the workload is cut dramatically as qualifications are issued by a University and encrypted onto the blockchain. Employers can then use the service to verify qualifications of a candidate.

Key benefits: Increased trust – records on the blockchain are in principle immutable (although in practice some applications have been subject to hacking). Reduced administration costs – the labour cost can be cut by more than a third.

Relevance to CCS: Compliance with storage regulations (such as the EU CCS Directive) and carbon trading systems requirements (such as the EU Emissions Trading System) requires verification of stored carbon. Distributed ledgers and smart contracts could provide a solution with low administrative burden for verification and trading on a large scale; however, it is likely that the system will need to be accepted by the relevant governing bodies.

2.2.4 Virtual reality and Augmented reality (VR/AR)

The terms Virtual and Augmented Reality describe a spectrum of technologies which enhance perception:

- **Virtual Reality (VR)** describes technology which immerses users in a fully virtual environment. This allows users to experience and interact with a fully simulated world, testing out designs and allowing enhanced understanding of the impact of different user interactions.
- **Augmented reality (AR)** overlays virtual objects or signals on the real-world environment, enhancing the information available to users. This can be done through anchoring virtual objects to real world objects, for example, a graph of sensor data can be superimposed on the plant it is monitoring to enhance inspection.

These technologies rely strongly on advances in other digital technologies, incorporating large amounts of computing power, detailed sensor data, and advanced systems to display and interact with these virtual objects. For both VR and AR, visual feedback through headsets or glasses is the most common form of interaction, but auditory, motion and haptic (touch) feedback is also possible[68].

Applications of VR and AR are typically in simulation, training, and data visualisation, as well as in enhanced inspection and maintenance. VR and AR rely on digital systems and IoT platforms to manage and distribute data and require developments in low-cost advanced wearables to become widely deployed. As display technologies, data processing and simulation technologies advance, more areas within industry will be able to utilise VR and AR.

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[66] https://www.gradba.se/en/
[67] https://medium.com/gradbase-blog/how-top-universities-in-the-uk-could-be-70k-better-off-every-year-with-blockchain-based-diplomas-ba8224c79fd5
[68] https://people.rennes.inria.fr/Anatole.Lecuyer/ipt2002.pdf

Relevant applications for CCS

The applications of VR/AR in CCS are expected to be very similar to those in other sectors. These applications are summarised in Table 2-4.

Table 2-4 Summary of relevant applications of virtual reality and augmented reality and their benefits

Application	Description	Key benefits
Enhanced Inspection and maintenance	AR equipment allows data from plant sensors to be displayed when inspecting equipment, giving operators access to available data in real time[69]. AR can also connect local technicians to remote experts, allowing repair work to be carried out without the need for experts to be physically present on site (*see Case Study 8).*	- **Reduced labour costs** of monitoring and inspection due to reduced time in accessing information - **Decreased downtime** from critical failures - **Reduced maintenance costs** through reducing travel to a site
Enhanced design	VR in association with CAD helps designers and operators understand and iterate how buildings[70], plant and equipment[71] will operate before prototyping/construction begins, improving the final design[72].	- **Reduced cost and time** for plant design and commissioning
Remote/improved operation of equipment	VR can help operate equipment remotely, for example robots in harsh environments and underwater[73].	- **Increased operator safety** (operation in harsh environments) - **Reduced labour costs** by replacing workers in offshore locations
VR Training	VR can give operators the chance to gain additional experience in a simulated plant environment[74,75], as well as controlled experience under difference scenarios/emergencies[76]	- **Reduced costs** of staff training - **Increased standards** of staff safety and training

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[69] https://www.dhl.com/en/press/releases/releases_2015/logistics/dhl_successfully_tests_augmented_reality_application_in_warehouse.html
[70] https://www.pbctoday.co.uk/news/bim-news/virtual-reality-designs-buildings/32045/
[71] https://www.forbes.com/sites/leoking/2014/05/03/ford-where-virtual-reality-is-already-manufacturing-reality/#11cafa6f6e4d
[72] https://www.virtalis.com/case-studies/visionary-render-enables-rolls-royce-to-explore-new-approaches-to-design/
[73] https://pale.blue/simulators/subsea-and-diving/vr-rov-simulator/
[74] https://www.visionthree.com/siemens-vr-training
[75] https://www.ludus-vr.com/en/areas/industry/
[76] https://www.forbes.com/sites/charliefink/2017/10/30/vr-training-next-generation-of-workers/#4f0e3fe464f5

Case Study 8 - Enhanced maintenance[77]

Image credit: VRMedia

Sector: Oil and gas

Application: Baker Hughes used an AR helmet to replace parts of a turbine at a petrochemical plant in Malaysia. Conventional maintenance would have required flying a US crew to the site and a 10-day shutdown in operations. Using the helmet required only 5 days shutdown and one local technician, guided remotely by the US team.

Key benefits: Reduced downtime and reduced costs – sending the US team would have cost $50,000, that was avoided. Cost reductions for some corrective maintenance interventions are estimated to be up to 30-40%.

Relevance for CCS: Remote operation and assistance is particularly relevant for offshore operations where cost-savings can be realised through limiting the number of crew required for maintenance visits. However, AR will also be beneficial wherever critical equipment maintenance requires external expertise or would benefit from access to key documentation in real-time.

2.2.5 Additive manufacturing

Additive manufacturing is the process of creating objects via layer by layer deposition of material (also called 3D printing). A range of different materials can be deposited, including plastics, ceramics, metals and metal-alloys. A range of additive manufacturing techniques can be employed to create products at different length scales (from few millimetres to many metres) and resolution (micron to millimetre). Additive manufacturing is enabled by software techniques, including CAD, computer-aided-manufacturing (CAM) and computer-aided engineering (CAE), and improvements in all tools are needed to fully realise its potential.

The likely use cases for additive manufacturing are shaped by the advantages the technology has over traditional manufacturing:

- Due to the additive nature of the process, **complex geometries** are possible that either couldn't previously be achieved or couldn't be achieved cost-effectively with conventional manufacturing techniques. This removes constraints of conventional design, allowing for optimisation driven only by functionality.
- Only the required material is deposited, reducing the need for machining and resulting in **less material waste**. This is particularly attractive for parts made from high value materials.
- Complete or near-complete components can be printed, **reducing the number of parts** and resulting in improved durability and performance.
- The products are made using a **general production mechanism**, so manufacturing lines can be switched between products quickly and easily, without the high initial costs and long lead times associated with traditional manufacture (such as production of moulds for injection moulding).

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[77] https://www.constructionequipment.com/ar-helmet-goggles-help-fix-remote-oil-field-equipment

The cost of manufacture by additive manufacturing may be either higher or lower than traditional manufacturing but value is delivered through gains in performance and time; as such, the cost-benefit considerations for using additive manufacturing are particularly application-dependent and difficult to generalise.

Relevant applications for CCS

The benefits of additive manufacturing are transferable to CCS, and its use for improving capture technology is already under development, targeting novel geometries for the capture materials themselves,[78] heat exchangers[79] and gas-liquid contacting columns.[80, 81] The main advantages offered by 3D printing for CCS are the ability to print materials with high surface area to volume ratios and smaller footprints. These features reduce the process size, increase productivity and, for solvent-based applications, reduce the required solvent inventory. More efficient heat exchange through the solvent column reduces degradation and aims to reduce emissions and waste treatment costs.

Additional applications within CCS are expected to be similar to those in other sectors. All relevant applications of additive manufacturing are summarised in Table 2-5.

Table 2-5 Summary of relevant applications of additive manufacturing and their key benefits

Application	Description	Benefit
Rapid prototyping	The combination of rapid manufacture and CAD allows designers to produce and adjust prototypes in a matter of hours. This enables a streamlined design stage where engineers can interact with and iterate a real, operable prototype. Prototyping has also been used in offshore oil and gas operations to test construction procedures before installation.	• **Reduced product development time** • Reduced project time reduces **financial risk** • Reduced cost of **prototyping/initial testing**
Spare part manufacture	Additive manufacturing can be used to print spare parts on or off site from a small stock of materials as and when required, eliminating the need for large spare part inventories or long lead times in sourcing parts. This is being integrated into many supply chains such as manufacturing and oil and gas.[82]	• Lower **sunk capital** in spare parts • **Reduced lead time** and (where relevant) **reduced import costs** for supply of spare parts to remote locations

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[78] https://3d-caps.eu/

[79] https://www.netl.doe.gov/sites/default/files/netl-file/X-Sun-ORNL-Additive-Manufacturing-Utilization.pdf

[80] J. E. Bara *et al.* Nanomaterials and Energy (2013) Vol 2 Issue NME5

[81] https://www.netl.doe.gov/sites/default/files/netl-file/E-Meuleman-ION-Rapid-Design-and-Testing-of-Contacting-Devices.pdf

[82] https://www.ecnmag.com/article/2016/02/rapid-prototyping-new-world-opportunities-oil-gas-industry

Component optimisation	Additive manufacturing has been used across a range of industrial sectors, including aviation (*see Case Study 9),* communications[83], and electronics[84] to improve design of components. Current applications in CCS focus on improvements to capture technology (see main text for details).	- **Reduced maintenance cost and increased lifetime** due to better part reliability - **Increased performance** due to optimised design - **Reduced cost** of equipment (lower weight of materials)

Case Study 9 - Novel geometries and design[85, 86]

Image credit: GE

Sector: Aviation

Application: GE have used additive manufacturing to improve engine performance, including printing fuel nozzles (LEAP engine) and TiAl turbine blades (GE9X). In the Advanced Turboprop (ATP) engine, additive manufacturing enabled the number of parts to be reduced from 855 to 12, resulting in more than of a third of the engine being 3D printed. Rapid prototyping during design reduced development time by a third.

Key benefits: Improved performance and lower operational costs – the ATP engine is 5% lighter, consumes 20% less fuel and achieves 10% more power than competitors, whereas the 3D-printed fuel nozzles in the LEAP engine result in 15% better fuel efficiency. Reduced opportunity for delay due to a simplified supply chain.

Relevance for CCS: Additive manufacturing is already being investigated for components of the capture process, targeting higher surface to volume ratios for gas-liquid contactors and improved heat exchange geometries. Rapid prototyping has already been beneficial in development times for these applications. Improved durability and efficiency in moving components such as compressors are a possible future application of additive manufacturing in CCS.

2.2.6 Advanced materials

We have considered two categories of advanced materials in our assessment:

Nanomaterials: Nanomaterials are materials with at least one dimension on the nanometre (10^{-9} m) scale. Applications of nanomaterials span a wide range of sectors, targeting improvements in structural materials properties (e.g. nanocomposites), catalyst performance, optical properties (e.g. quantum dots), and sensing, among others. In the oil

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[83] https://3dprintingindustry.com/news/optisys-reducing-antenna-parts-99-3d-printing-simulation-software-116509/

[84] https://www.designnews.com/automation-motion-control/additive-manufacturing-can-reduce-part-counts-significantly/32852757559475

[85] https://www.ge.com/reports/epiphany-disruption-ge-additive-chief-explains-3d-printing-will-upend-manufacturing/

[86] https://www.ge.com/reports/quiet-ascent-new-leap-engines-giving-lift-aviation-industry/

and gas sector, nanomaterials are used in surface coatings and catalysts for refining and have been investigated to improve enhanced oil recovery (EOR).

The main benefits of nanomaterials derive from their high surface area to volume ratio and include higher performance, novel functionality and strong surface interactions

Composites: Composites are materials that combine two or more different materials to generate improved functionality, for example carbon fibre and plastics. They are established in a number of industries and deployed widely, for example carbon fibre in manufacture to produce high strength, light materials. Composites enable reductions in materials cost through lower cost components and lower weight and improved functionality.

Relevant applications for CCS

Although both nanomaterials and composite materials may have a wide range of applications for materials and process improvement as well as for CO_2 utilisation[87], in this study, we have focused on two primary applications, as summarised in Table 2-6.

Table 2-6 Summary of relevant applications of advanced materials considered in this study

Application	Description	Benefit
Subsurface wetting	The surface properties of silica and other nanoparticles can improve the wettability and permeability of water and CO_2 in rock formations when injected alongside the CO_2. For EOR, this aids displacement of oil.[88] For CCS, this can enhance the amount of CO_2 stored.[89]	• **Increased reservoir exploitation** corresponding to increased revenue in the oil and gas industry and increased storage capacity for CCS
Composite pipes	Composites can replace or protect steel in pipelines, preventing or reducing corrosion behaviour. Composites are unlikely to be suitable for replacing large gas transmission pipelines; however, in the oil and gas industry, flexible composite pipelines are being trialled for flowlines, risers, jumpers and other subsea lines.[90] These pipelines are prepared by an additive manufacturing process of fibre-reinforced plastic deposition. The material is corrosion-resistant, and cheaper and easier to transport than steel.	• **Reduced capital costs** through ease of installations and transport • **Reduced maintenance costs** through reduced corrosion • **Higher tolerance** of impurities or corrosive material in pipeline

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[87] For example, a range of nanomaterials catalysts are being explored for CO_2 conversion to other chemical products

[88] M. Agista *et al.* Applied Sciences (2018) doi: 10.3390/app8060871

[89] S. Al-Anssari *et al.* International Journal of Greenhouse Gas Control (2017) doi: 10.1016/j.ijggc.2017.09.008

[90] https://www.dnvgl.com/oilgas/perspectives/composites-to-cut-subsea-costs.html

2.3 Technology readiness levels (TRLs) and development timescales

Technology readiness level (TRL) is a framework to assess and illustrate the commercial maturity of technologies. For each of these technology applications TRLs were estimated based on literature review of current industry usage and information from expert stakeholders. Here, the EU Horizon 2020 scale for TRL, shown in Figure 2-1, is used.

1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment
6	Technology demonstrated in relevant environment
7	System prototype demonstrated in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

Figure 2-1 EU Horizon 2020 TRL Scale

Although progress through the different TRL levels is highly technology dependent and varies widely on a case by case basis, research indicates the following assumptions for commercialisation timescales are appropriate[91]:

- TRL 1-3: 15-20 years
- TRL 4-6: 5-10 years
- TRL 7-9: less than 5 years

The estimated TRLs for the emerging technology applications within the different groupings are summarised in Figure 2-2. These are shown as ranges, as each ‘application’ refers to a complex variety of interlinked use cases and, as such, some are more mature than others. The ranges used are also intended to reflect that, while some technologies may be mature and deployed in other sectors, relevant applications in CCS require further development.

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[91] Peisen, D. J. and C. L. Schulz (1999). Case Studies: Time Required to Mature Aeronautic Technologies to Operational Readiness. Jenkintown, Pennsylvania, SAIC.

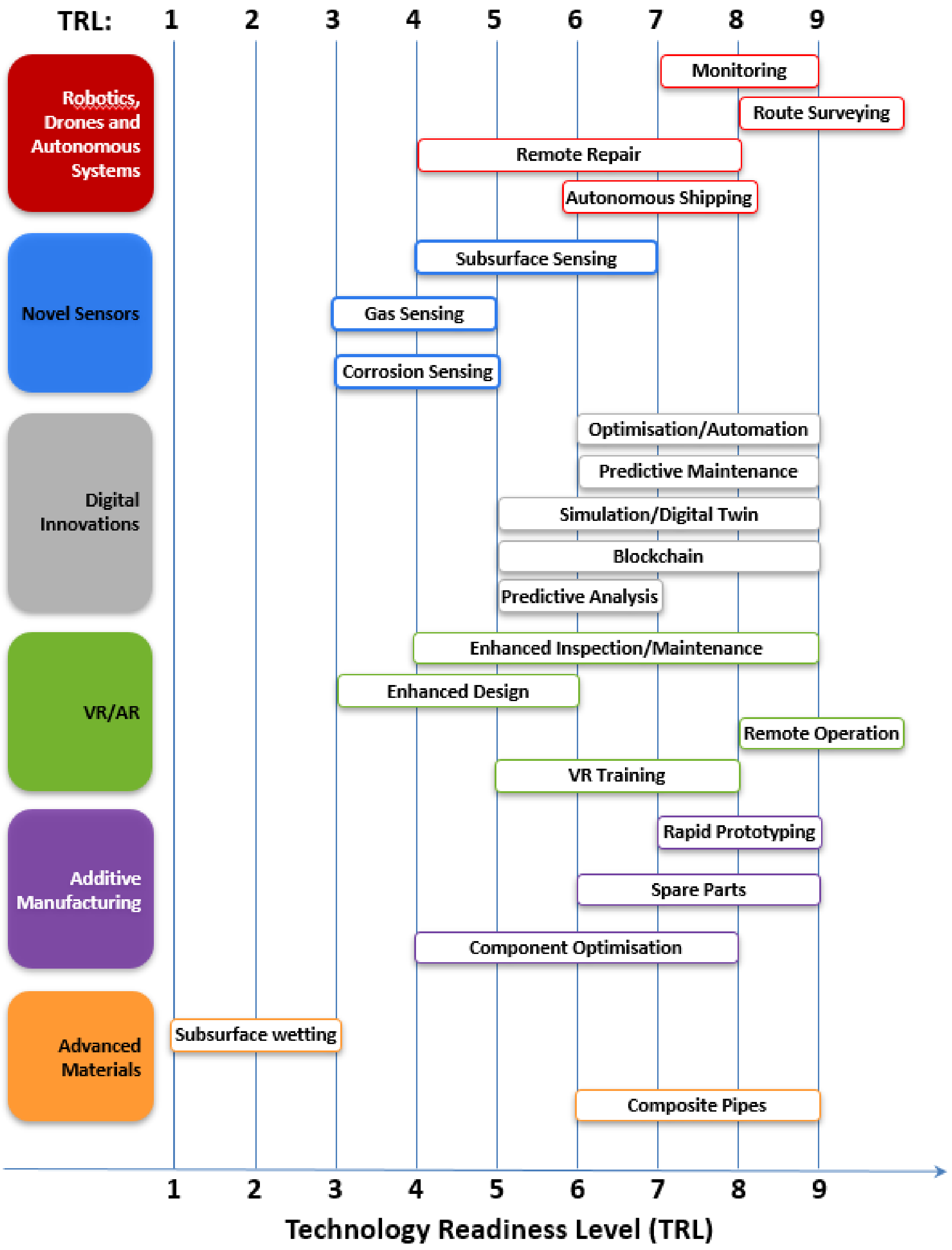

Figure 2-2 Estimated Technology Readiness Levels (TRLs) for digital and emerging technology applications

2.4 Costs, risks and challenges for deployment of digital and enabling technologies

Costs

The costs of implementing digital and enabling technologies ranges widely across applications and are not easily generalisable. However, some illustrative examples are as follows:

For robotics and drones, costs range from $1,000-2,000 for devices equipped with cameras, to $10,000's for drones with advanced sensors, and up to $100,000's for highly advanced equipment. The costs of these devices are expected to reduce as the cost of the components reduce. Where devices require an operator, some labour cost will also be incurred. However, many companies offer monitoring and surveying services, which results in a lower but on-going operational cost for industry organisations.

For sensor networks for leak detection, the cost depends on the number and configuration of sensors as well as the type; however, equipment costs of around €30,000 per km have been estimated for sensors deployed along a pipeline.[37]

For a **machine learning** project, development costs on the order of £100,000's may be expected, based on a UK funded research project.[92]

For Additive Manufacturing: Capital costs for installing a 3D printer on-site can range from €20,000 to €6.5m, depending on the deposition process and material, with costs increasing with increased complexity and resolution. However, many additive manufacturing service bureaus exist that offer printing of parts without the cost of buying a printer.

In addition to the technology cost, digital technologies require large amounts of data processing and storage capabilities. These additional costs can reach $1m for very large datasets.[93]

Risks and challenges to deployment of digital and enabling technologies

In addition to bringing benefits to projects, the uptake of digital and enabling technologies is also subject to risks and challenges.

Key risks for digitalisation of processes include:

- **Digital Failure** – The key risk of introducing digital technologies is a shutdown of the CCS network caused by a digital failure. While digital technologies can reduce the risk of some system failures (such as through predictive maintenance), they also create additional points of failure through increased connectivity and vulnerability to cyberattacks. To combat this, systems should be built robustly with sufficient redundancy, and organisations need increased understanding of cybersecurity risks[94].

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[92] Based on £500,000 total project cost, with ~£100,000 for the software development team https://gtr.ukri.org/projects?ref=102492

[93] https://www.forbes.com/sites/ciocentral/2012/04/16/the-big-cost-of-big-data/#cf1743c5a3b7

[94] https://www.enisa.europa.eu/news/enisa-news/cybersecurity-is-a-key-enabler-for-industry-4-0-adoption

- **System security –** with increasing numbers of processes controlled digitally, there is an increased vulnerability of industries to hacking. While cyber-attacks cannot be fully prevented, security and resilience have to be considered in the design of any digital system[95].
- **Data speed and connectivity** – digital technologies generate enormous amounts of data and rely on data exchange. Lack of coverage in remote areas where technology applications (such as drones and autonomous ships) are particularly useful is a challenge. Wireless technology such as 5G is an enabler of these systems, as are technology developments such as data hopping (data transmission between robots).
- **Accountability and trustworthiness –** with processes and decision-making either augmented by or undertaken completely using AI, stakeholders must be able to trust and understand the processes behind these decisions. AI needs to be interpretable and then explainable to avoid issues with regulation and unintentional bias[96,97].
- **System integration –** the use of non-standard sensor networks can make it difficult to integrate separate systems and to view data on a common interface.[98] As such, design of whole-system solutions at the outset of a project is advantageous.
- **Employment impacts –** replacement of highly predictable, routine, manual tasks with automated processes comes with associated risks of job losses for workers in these sectors;[7] however, digitalisation also has the potential to create jobs and the associated upskilling of the workforce has the potential to attract a wider range of employees than traditional roles.[99,100]

Additional barriers to uptake of digital and enabling technologies include:

- **Industry acceptance** – operators and project developers are often reluctant to accept novel technologies. Proving the technologies' value, enabling increased familiarity with technologies and addressing skills shortages will help address this barrier[101]. This is a particular barrier for new materials and processes such as additive manufacturing and composite pipelines.
- **Standardisation** – implementing new materials or methods in projects relies in part on the development of standards that include these technologies (e.g. inspection standards and materials standards), which can lag behind technology development. This is particularly the case for additive manufacturing, and for new materials such as composite pipelines[102].

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[95] A.R. Sadeghi, *et al.* "Security and privacy challenges in industrial internet of things", *Design Automation Conference (DAC) 2015 52nd ACM/EDAC/IEEE*, pp. 1-6, 2015, doi: 10.1145/2744769.2747942.

[96] *An Intelligence in Our Image: The Risks of Bias and Errors in Artificial Intelligence* (2017) RAND

[97] https://www.pwc.co.uk/services/risk-assurance/insights/explainable-ai.html

[98] *CCSA: A Cloud Computing Service Architecture for Sensor Networks* (2012) DOI: 10.1109/CSC.2012.12

[99] https://www.theguardian.com/business/2018/apr/02/robot-heads-for-north-sea-oil-rigs-in-world-first-scheme

[100] https://www.offshore-technology.com/features/the-oil-industrys-best-kept-secret-advice-from-women-in-oil-and-gas/

[101] https://www.bcg.com/publications/2015/engineered_products_project_business_industry_4_future_productivity_growth_manufacturing_industries.aspx

[102] Monzón, M.D. et al. Int J Adv Manuf Technol (2015) 76: 1111 doi:10.1007/s00170-014-6334-1

- **Skills or Talent Shortage** – Lack of personnel with the appropriate skills for implementation and use of emerging technologies, particularly digital technologies, is a key barrier to increasing the uptake of emerging technologies[103].
- **Unproven materials –** particularly for nanomaterials, applications are still at an early stage of development with unproven behaviour in large-scale operations or in reservoir conditions. The technical uncertainty in using these materials is high, and long testing periods will be required before their use is accepted. For nanomaterials, uncertainty over safety of their use and release into the environment is also a barrier to deployment.[104]

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[103] *Digital Skills for the UK Economy* (2016) Ecorys for UK Government

[104] Gottschalk F, Nowack B (2011) Release of engineered nanomaterials to the environment. J Environ Monit 13:1145–1155

3 Potential impact of emerging technologies on CCS projects

This study aims to assess the potential impact of emerging technologies on CCS projects, both in terms of the quantitative impact on costs and the qualitative impact on risks and challenges.

Since applications of technologies vary across capture, transport and storage, each element of the CCS chain was considered separately. Each element of the CCS chain was broken down into representative processes and the impact of the emerging technologies on each of these processes was assessed (described in more detail in Section 3.1.2 for the cost modelling). The analysis was based on currently mature processes and technologies; novel technologies or approaches under development – such as novel, unproven capture materials or modularisation – were not included in the quantitative analysis. However, these technologies are potentially disruptive and are treated qualitatively in Section 3.3.

3.1 Impact of emerging technologies on costs

3.1.1 Applications of emerging technologies across the CCS chain

Based on the information gathered in Chapter 2, 17 categories of technology applications were considered in our cost modelling. These are summarised in Table 3-1 and described in detail in Section 6.1 (page 50). Unforeseen highly radical and disruptive advances from these technologies are not assumed in this study but cannot be ruled out in practice.

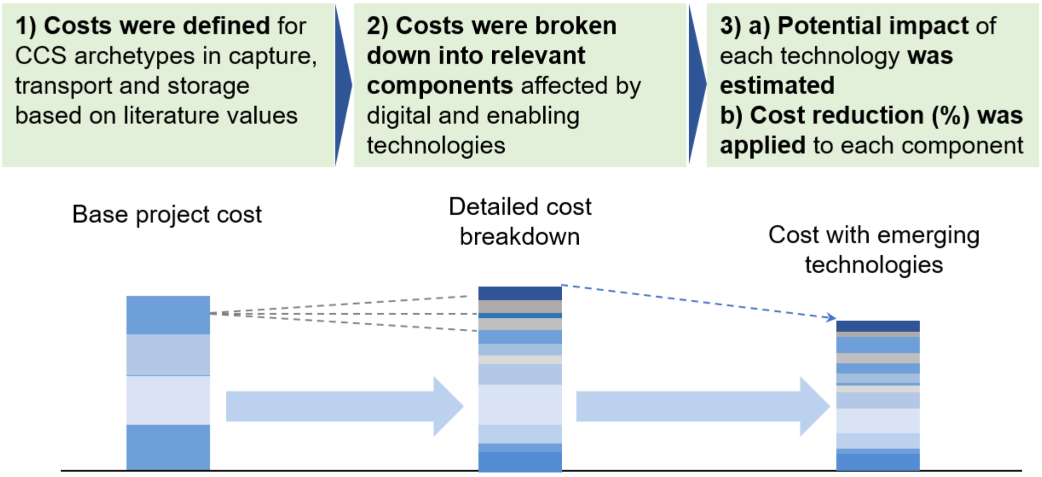
Table 3-1 Summary of emerging technology applications across the CCS chain

		Relevant chain element		
Technology group	**Application**	**Capture**	**Transport**	**Storage**
Robotics, drones and autonomous systems	Asset inspection	🟩	🟩	🟩
	Remote repair		🟩	
	Autonomous ships		🟩	
Novel sensors	CO$_2$ detection	🟩	🟩	🟩
	Subsurface sensing			🟩
	Corrosion sensing			🟩
Digital innovations	Automation and optimisation	🟩	🟩	🟩
	Predictive maintenance	🟩	🟩	🟩
	Advanced analysis			🟩
	Predictive analysis			🟩
	Virtual commissioning	🟩		🟩
	Distributed ledgers	🟩		

VR/AR	Enhanced inspection	🟩		🟩
	Enhanced training	🟩		🟩
Additive manufacturing	Enhanced design and performance	🟩		
	Spare part printing	🟩		🟩
Advanced materials	Composite pipelines for injection			🟩

3.1.2 Cost modelling methodology

The approach for the cost modelling is summarised in Figure 3-1



1) Costs were defined for CCS archetypes in capture, transport and storage based on literature values

2) Costs were broken down into relevant components affected by digital and enabling technologies

3) a) Potential impact of each technology **was estimated**
b) Cost reduction (%) was applied to each component

Figure 3-1 Schematic representation of cost modelling methodology (illustrative only)

Counterfactual costs

Representative archetypes for each element of the CCS chain were defined and modelled based on literature data. Capture costs included the capture technology and compression for onward transport. Aspects of transmission of CO_2 from the capture plant to the storage site were considered under Transport. Storage costs consider only the development, operation and post-closure monitoring of the storage site itself. For the detailed cost assumptions, see section 6.1, page 55.

Capture costs were modelled for representative examples of CCS technologies within power CCS, industrial CCS and fuel transformation:

- **For the power sector**, supercritical pulverised coal (PC Supercritical) and natural gas combined cycle (NGCC) plants were chosen as examples of more mature (post-combustion) technologies with globally significant feedstocks.
- **For industrial CCS**, cement, and iron and steel plants were chosen as examples of industries with flue gas emissions that require CO_2 capture technology; Ammonia production was included as an example where a pure CO_2 stream is produced as part of the process, and therefore the required capture equipment is much simpler.
- **For fuel transformation**, natural gas processing and bioethanol production were included, both of which produce a pure CO_2 stream.

First-of-a-kind (FOAK) plant costs for each plant type were taken from Global CCS Institute figures,[105] assuming mature capture technology (first generation amines). Nth-of-a-kind (NOAK) plants were modelled as deploying the best available technology (second generation amines for power CCS, calcium looping for iron and steel and cement plants).[106]

Transport costs were modelled for onshore and offshore pipelines and CO_2 shipping. For each mode of transport, the reference cases were chosen to represent conditions of cost-effective deployment.

Storage costs focused on saline aquifers (SAs) as the storage option with the greatest potential global storage capacity but also the highest cost.[107] Liability transfer costs were included in the cost modelling to represent the risks associated with long-term storage management.

No cost reductions were assumed for transport and storage over time, since the majority of cost reductions are expected to derive from economies of scale for shared transport and storage networks. This is in line with projections from other organisations[108] but, in reality, some effect of learning rates is likely with increased deployment.

All costs were converted to $2015 price base, and a 10% discount rate was applied in line with previous studies.[109]

Detailed cost components for assessing impact

The base counterfactual project costs were broken down into the relevant components expected to be affected by digital and enabling technologies based on CCS literature and FEED reports, or estimation based on information from relevant related sectors (such as oil and gas). The detailed assumptions are summarised in section 6.3, page 55.

To quantify some of the additional benefits offered by the technologies, further cost components were defined and added to the base costs:

- **Downtime –** represents time when a facility is not in operation due to equipment failure or planned maintenance. For a capture site, it is assumed that the emitting plant continues to operate but the CO_2 that would have been captured is vented to air. For a storage facility, it is assumed that the CO_2 that would have been injected is either vented to air or alternative storage arrangements must be made. As such, downtime is represented as a cost of additional carbon emitted during downtime, by applying a carbon price in line with IEA projections.[110] Capture and storage sites are assumed to incur the cost of emissions arising from all unplanned downtime,[111] assuming that planned downtime can largely be coordinated both with the emitting plant and across the CCS chain; pipelines are assumed to be reliable and therefore only experience negligible downtime
- **Supply chain losses –** represent loss of CO_2 across the supply chain through leakage from infrastructure. This represents a general chain-wide loss and is not an indication of any expectation of leakage from permanent storage. CO_2 loss is

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[105] *Global Costs of Carbon Capture and Storage –2017 update* (2017) GCCSI
[106] *Extension to Fuel Switching Engagement Study (FSES) Deep decarbonisation of UK industries* (2019) Element Energy for the Committee on Climate Change
[107] *The Cost of CO_2 Storage* (2011) Zero Emissions Platform
[108] Personal communication, International Energy Agency
[109] For example, see *Projected Costs of Generating Electricity* (2015) International Energy Agency
[110] The carbon price was set at $50/t$CO_2$ in 2025 and rising to $140/t$CO_2$ by 2040, in line with the average value in the 2°C Scenario, from *World Energy Outlook* (2018) International Energy Agency
[111] Set to be 20 days per year for capture plants and 6 days per year for storage sites, based on typical power plant and oil rig downtime

assumed to be 1% of capacity, based on leakage rates for the natural gas industry.[112] For simplicity, this is divided equally across the CCS chain (0.33% for capture, transport and storage); however, this is likely to be an overestimate both since the infrastructure is modern, and because the likelihood of leaks is known to vary across the chain. As for downtime, supply chain loss is represented as a cost of released carbon.

- **Verification of carbon stored –** represents the cost to a facility associated with complying with CCS certification schemes. Although compliance with such schemes will be required by all actors in the CCS chain, verification costs were only applied to capture plants since this was the part of the chain expected to have the largest administrative burden. A cost of $\$0.10/tCO_2$ was applied, based on the UK industry average cost of EU Emissions Trading System reporting.[113]

Cost reductions due to emerging technologies

Percentage cost reductions were defined for each emerging technology application through comparison with case studies in relevant applications or literature reports or projections. Cost reductions were defined for three project **operational start dates** to account for progression in technology development:

- **2025**: FOAK projects either already undergoing or having recently completed front-end engineering (FEED) and entering the construction stage – only applications of digital and enabling technologies that are currently in use and that affect operational costs are considered applicable.
- **2030:** NOAK projects, starting FEED within the next 2-5 years (2021-2025), with the opportunity to implement some technologies during design and construction.
- **2040:** NOAK projects starting FEED within the next 15 years (by 2035), when all of the considered technological advancements are expected to be available

For full details of the modelling inputs, see section 6.4, page 58.

Where the impact of a technology application was not generalisable, such as for additive manufacturing, broader estimates were applied based on relative equipment costs[114] or performance; for example, the impact of a 3D-printed component increasing compressor efficiency on fuel costs was estimated by calculating the associated decrease in energy requirement (assuming an increase in efficiency of 5-10%).

Additional costs of the digital and enabling technologies were accounted for in the cost reduction estimates. In many cases, the cost reductions described in case studies and literature reports include the difference in technology cost; where this was not explicitly the case, the percentage cost reductions were adjusted to account for the additional cost. However, for many technologies, the additional costs were negligible compared to the lifetime costs of the respective CCS chain element[115]

For simplicity, the technological applications were assumed to be static over time once the plant or facility is built, with no new developments added after operation begins. The

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[112] *Inventory of U.S. Greenhouse Gas Emissions and Sinks:1990-2016* (2018) EPA

[113] *Assessing the cost to UK operators of compliance with the EU Emissions Trading System* (2010) Aether

[114] Based on available literature within CCS or relevant related sectors

[115] For example, the cost of a robot may range from $2,000 - $200,000, with similar lifetime maintenance costs, but this corresponds to much less than $\$0.1/tCO_2$ of a project lifetime cost (less than 1% of the lifetime cost of a capture plant)

exception is for post-closure monitoring of storage sites, since this phase occurs very late in the project lifetime. For monitoring or maintenance applications across the rest of the CCS chain this assumption likely to be an oversimplification but, in the case of digital systems such as AI and Internet of Things (IoT), designing smart systems at the outset is likely to be more cost-effective than later retrofitting.

The estimated cost reductions were then applied to the relevant counterfactual cost components to calculate the overall impact on the total lifetime cost of each of the CCS chain elements. Both the impact of each technology alone and the collective impact of all technologies were assessed. In estimating the collective impacts of all applications, the cost reductions were assumed to be multiplicative, since the technologies largely do not compete (one does not make another obsolete).[116]

3.1.3 Projected cost reductions

Costs were modelled for the counterfactual archetypes both with and without digital and emerging technologies. It should be noted that cost projections for immature technologies and/or novel applications are inherently uncertain and therefore the cost savings presented here should be interpreted as an illustrative case. Uncertainties in the analysis are described and analysed in more detail in Section 3.1.6.

Capture

For capture plants, the total lifetime project costs are dominated by the capture technology. Since the majority of digital and enabling technology applications target opex costs, the expected overall impact of emerging technologies is small compared to the projected counterfactual cost reductions on going from FOAK (first generation amines) to NOAK (best available technology; Figure 3-2).

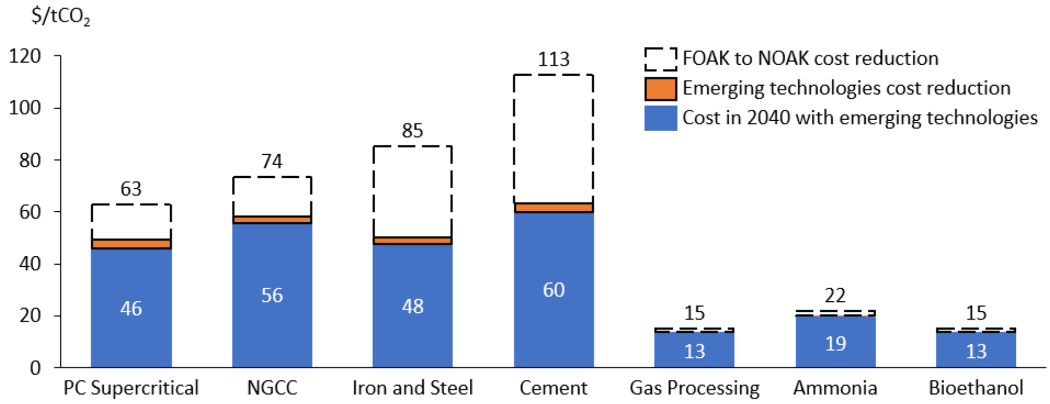

Figure 3-2 Reduction in capture plant project costs (capex, opex and fuel) on going from FOAK (in 2025) to NOAK (in 2040), and with all digital and enabling technologies applied to NOAK plants (in 2040).

For plants beginning operations in 2025, very few technologies are available and therefore only small reductions in lifetime project costs are projected (1-5%, equivalent to $1/tCO$_2$ for each type of plant). This rises to 7-15% in 2030 and 9-20% in 2040. In all cases, the lowest

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[116] For example, where capture plant maintenance costs were impacted by additive manufacturing (-5%), VR/AR (-10%) and predictive maintenance (-30%), the new component cost was 60% of the counterfactual (95%×90%×70%)

absolute cost savings, but highest percentage cost reductions, are for plants that generate a pure CO_2 stream (lowest counterfactual cost) and the highest absolute savings are for post-combustion plants. Cement plants experience the highest absolute cost savings.

However, more than half of these cost reductions for post-combustion plants are due to reductions in downtime (75-80% for plants with pure CO_2 streams), with only a 4-6% reduction in plant capex, opex and fuel use in 2040. For a coal power plant, these reductions represent (discounted) savings on the order of \$30m in capex, \$70m in opex and \$7m in fuel use over 20 years.

In 2025, the largest contribution to cost reductions in capex is due to replacing spare parts inventories with additive manufacturing. By 2030, additive manufacturing and digital innovations both reduce capex (1.2-1.5% reduction each), with reductions in process contingency through virtual commissioning a significant component.

In 2025, robotics, VR/AR and additive manufacturing all contribute to opex cost reductions; however, by 2040, digital innovations have by far the largest impact, both in plant operational costs and in costs of downtime (Figure 3-3). These savings are primarily associated with predictive maintenance, with digital innovations accounting for 56% of downtime and 86% of maintenance materials opex savings.[117]

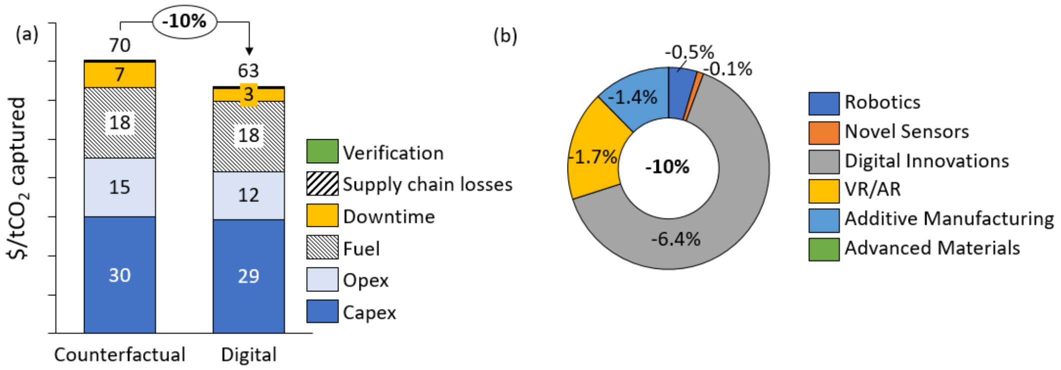

Figure 3-3 Projected cost reductions due to emerging technologies for a cement plant starting operations in 2040: (a) reductions in project cost components and (b) contributions of each emerging technology group. Values are quoted to one decimal place to highlight the relative scale only and should not be interpreted as a statement of cost certainty.

Pipeline transport

Pipeline costs are dominated by capex, whereas the primary impacts of emerging technologies for pipelines lie in opex reductions. As such, as for capture plants, only modest reductions in the base project costs are expected (Figure 3-4).

Overall cost reductions of less than 1% are expected for pipelines operating in 2025, rising to 4% for projects operating in 2040. Reduced supply chain losses of CO_2 make a significant contribution to the cost savings at all timepoints (accounting for 69% of the cost reduction for an onshore pipeline in 2040), with only a 1-2% decrease in the overall base cost

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[117] Based on a cement plant operating from 2040.

components by 2040; however, reductions in opex of 45% for onshore pipelines and 36% for offshore pipelines are projected for projects starting in 2040.

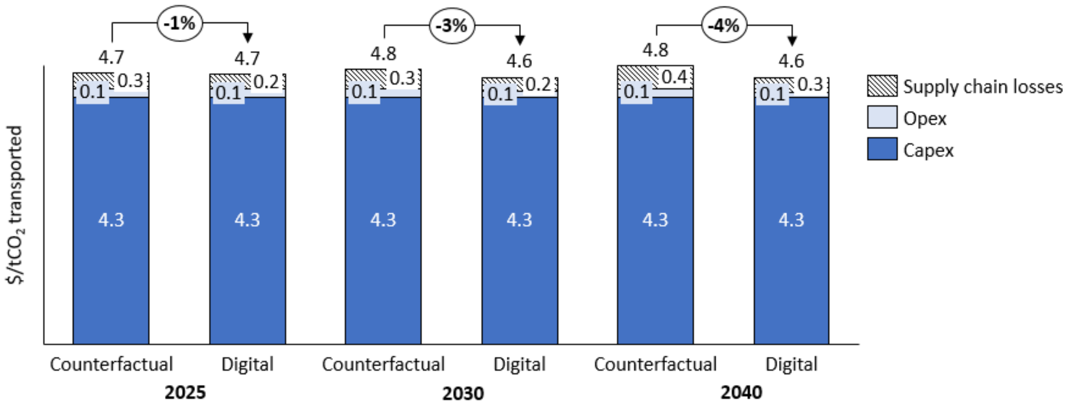

Figure 3-4 Projected cost reductions for an onshore pipeline due to emerging technologies; note that overall costs increase between 2025 and 2030 due to increases in the carbon price (affecting the cost of supply chain losses). Values are quoted to one decimal place to highlight the relative scale only and should not be interpreted as a statement of cost certainty.

The primary technologies driving overall cost reductions are novel sensors and robotics, in line with the contribution of supply chain losses to the overall cost analysis (Figure 3-5).

Robotics and digital innovations contribute the most to reductions in operational costs, with the largest impact expected for pipeline repair costs (with 60% due to applications of robotics). These cost savings are primarily associated with predictive maintenance and in situ repair using robot-enabled 3D printing.

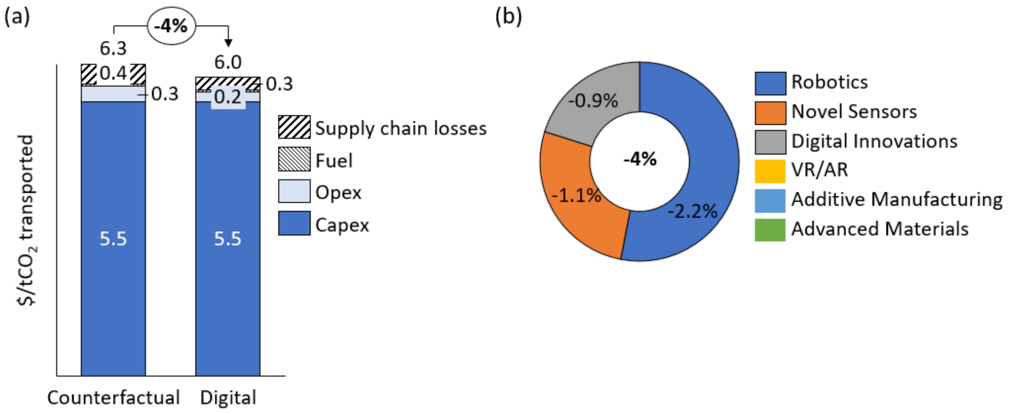

Figure 3-5 Projected cost reductions for an offshore pipeline operating from 2040: (a) breakdown of overall cost reduction and (b) contributions of each technology group. Values are quoted to one decimal place to highlight the relative scale only and should not be interpreted as a statement of cost certainty.

CO_2 Shipping

The introduction of autonomous ships dominates the potential cost reductions in shipping; however, with the discount factor applied, savings in ship operational costs (30% undiscounted; 19% discounted) are largely outweighed by the increase in ship capex (10%), resulting in only a 1% decrease in the (discounted) lifetime cost of the ship and the shipping chain (Figure 3-6). Autonomous shipping is therefore unlikely to impact the role that shipping is likely to play in the large-scale deployment of CCS.

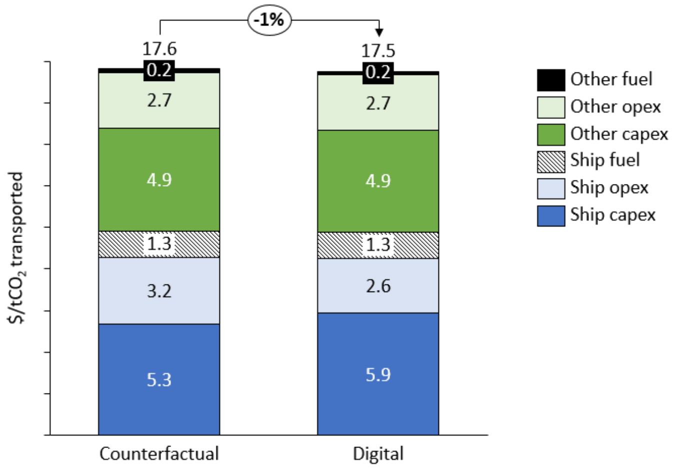

Figure 3-6 Projected cost reductions for a CO_2 shipping chain in 2040. Values are quoted to one decimal place to highlight the relative scale only and should not be interpreted as a statement of cost certainty.

Storage

CO_2 storage sites experience the most significant cost reductions from applications of emerging technologies.

For storage sites operating from 2025, overall reductions of 2% in lifetime costs are projected for both onshore and offshore sites, resulting from 8-9% reduction in opex and a 10% reduction in supply chain losses of CO_2.

By 2040, 19% (offshore) and 26% (onshore) overall cost reductions are projected, resulting from a 7-9% reduction in capex, 50% reduction in opex and 50% reduction in injection facility downtime (Figure 3-7 and Figure 3-8). For an offshore saline aquifer, these reductions in base costs correspond to over $45m saving in capex and close to $60m saving in opex for an offshore site.

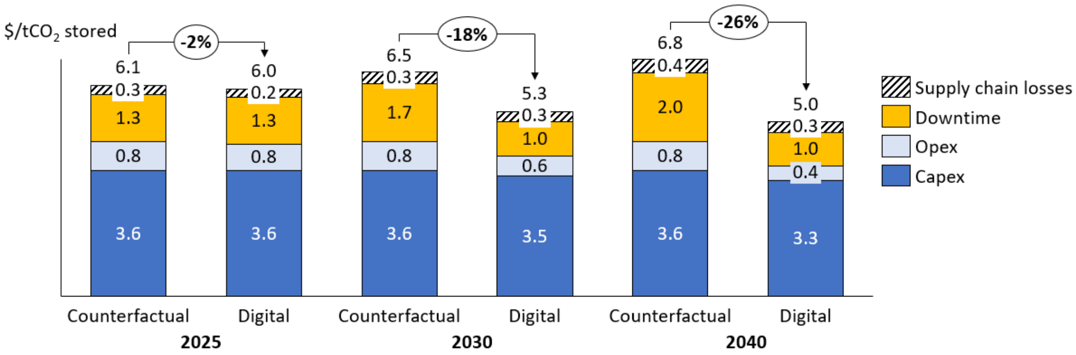

Figure 3-7 Projected cost reductions due to emerging technologies for an onshore saline aquifer over time; note that the lifetime cost for the counterfactual increases over time due to increases in the carbon price (affecting the cost of supply chain

losses and downtime). Values are quoted to one decimal place to highlight the relative scale only and should not be interpreted as a statement of cost certainty.

Digital innovations have the most significant impact on capex, opex and downtime costs, through automation and predictive maintenance. AI-powered drilling is expected to reduce injection well capex costs by 5%.

Site appraisal costs comprise both the costs of seismic surveying and the cost of drilling appraisal wells. An overall reduction in site appraisal costs of 23% is projected in 2040, resulting from a 40% reduction in seismic appraisal costs due to improvements in sensing (26%) and analysis (14%) and a 15% saving in the cost of appraisal well drilling due to advances in AI.

Composite pipelines contribute to 13% savings in capex and 11% savings in opex for a storage site in 2040.

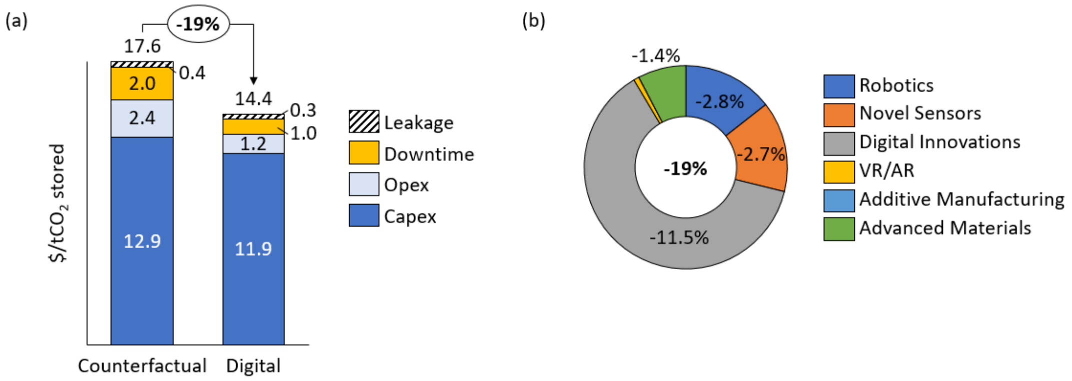

Figure 3-8 Projected cost reductions for an offshore saline aquifer starting operations in 2040: (a) breakdown of overall cost reduction and (b) contributions of each technology group. Values are quoted to one decimal place to highlight the relative scale only and should not be interpreted as a statement of cost certainty.

3.1.4 Relative impacts of technologies across the CCS chain

To compare the relative impacts of emerging technologies across the CCS chain, levelised cost savings over the project lifetime for a cement plant, 180km offshore pipeline and an offshore saline aquifer were compared. Across these three archetypes, a combined saving of \$11/tCO_2 (11%) is projected.[118] Of this cost reduction, 56% is in base capex or opex rather than savings in downtime and leakage, with the primary savings in capture and storage (Figure 3-9).

Of the ten cost components that experience the largest levelised cost reductions (\$/tCO_2), seven are either opex costs or emitted carbon costs (downtime and leakage; Figure 3-9). **Automation and predictive maintenance** affect all of these cost components; aside from reduced downtime, the largest saving is in capture plant maintenance opex (see also Figure 6-3, Appendix).

- **Robotics, drones and autonomous systems** deliver benefits across the chain, with the primary impact on downtime and leakage resulting from improved monitoring, maintenance and repair (Figure 6-1, Appendix).

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[118] It should be noted that this is not intended to be representative of any planned or existing real-world project but is for illustration purposes only

- The largest cost reduction due to **novel sensors** is in storage appraisal costs due to improved subsurface sensing (Figure 6-2, Appendix), with additional benefits in reducing leakage and downtime, and ongoing subsurface monitoring costs.
- **Additive manufacturing** is expected to have the greatest impact in capture downtime through spare part printing and increased reliability of components (Figure 6-5, Appendix).
- The primary cost impact of **VR/AR** across the chain is in reduced downtime (Figure 6-4, Appendix); however, additional benefits of data analysis and interpretation are not captured here.
- **Advanced materials** were only considered applicable in storage applications, with the greatest impact on injection facility capex (Figure 6-6, Appendix).

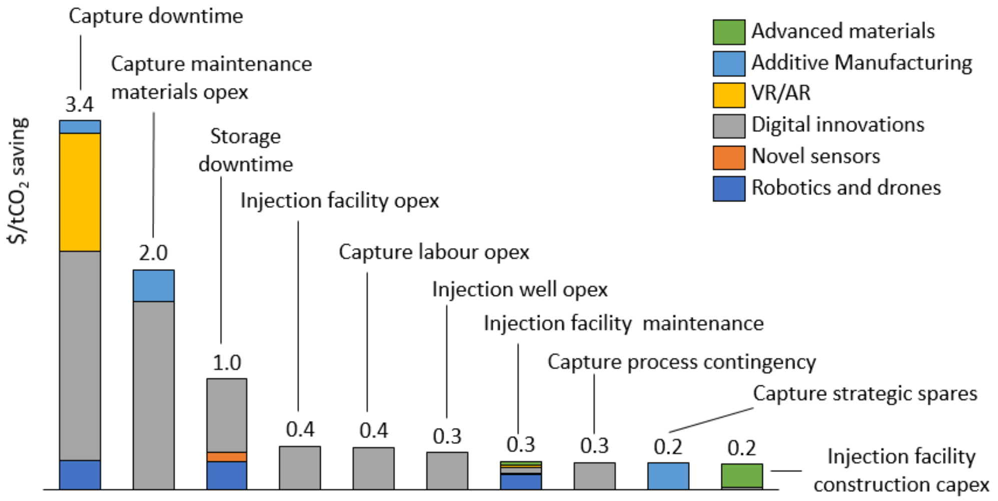

Figure 3-9 Comparison of magnitude of cost reductions due to emerging technologies across the CCS chain, based on capture from a cement plant, 180km offshore pipeline and storage in an offshore saline aquifer (all operating in 2040). Values are quoted to one decimal place to highlight the relative scale only and should not be interpreted as a statement of cost certainty.

3.1.5 Effect of discount rate

Cost modelling was carried out for representative archetypes across the CCS chain with a lower discount rate (4%) and with undiscounted (0%) costs. Lowering the discount rate increases the relative contribution of opex costs to the levelised lifetime cost and reduces the relative contribution of capex costs compared to the base case (10% discount rate). Since the primary impacts of digital and enabling technologies are in reducing opex costs, lowering the discount rate increases the overall cost reductions for each of the components of the CCS chain (Table 3-2 and Figure 3-10; see also Figure 6-7and Figure 6-8 for capture and pipeline transport).

Table 3-2 Effect of applied discount rate on projected reductions in levelised lifetime cost due to applications of digital and enabling technologies across the CCS chain in 2040

	Reduction in levelised lifetime cost at given discount rate		
Archetype	**0%**	**4%**	**10%**
Cement Plant	13%	12%	10%
Offshore pipeline	10%	7%	4%
CO_2 shipping	4%	2%	1%
Offshore saline aquifer	26%	23%	19%

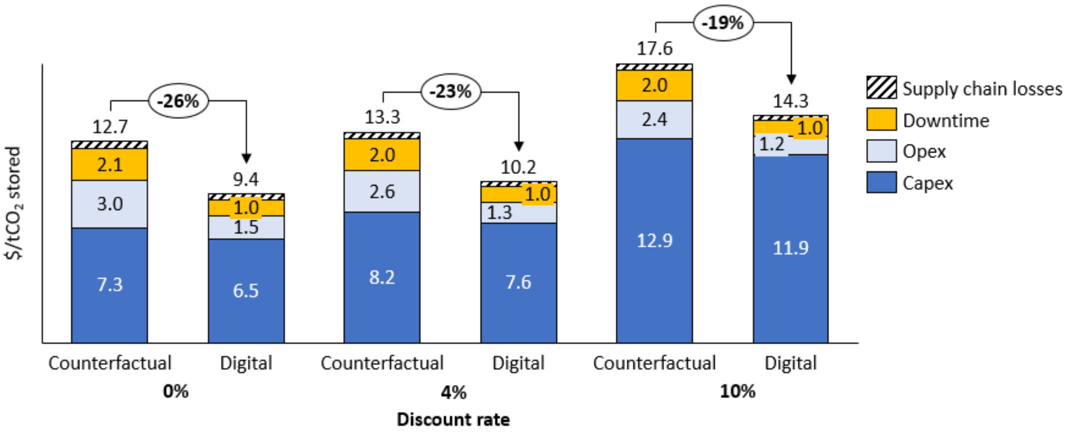

Figure 3-10 Effect of applied discount rate on projected reductions in levelised lifetime cost for an offshore saline aquifer operating in 2040. Values are quoted to one decimal place to highlight the relative scale only and should not be interpreted as a statement of cost certainty.

3.1.6 Uncertainty in cost projections

Although based on the best available data, there are significant uncertainties in all estimations of potential cost reductions due to both the immature technologies and incomparable applications, as well as the lack of extensive empirical data for CCS projects. Estimates of benefits from applications of additive manufacturing are particularly uncertain, since these are highly case-specific. Within this study, there was also limited data regarding the allocation of injection facility costs to the costs of pipelines, giving high uncertainty to the projections of cost reductions for composite pipelines.

The largest impacts on costs in this analysis are from automation and predictive maintenance; however, the degree to which CCS processes may already be automated varies across projects. As such, although 50% reductions (or higher) in labour costs are considered possible in some cases[119] the degree to which costs can be reduced through automation will vary from project to project. Similarly, the impact of predictive maintenance depends on the maintenance strategy currently employed by project operators. For example, the cost savings compared to reactive maintenance strategies (30-40% savings) are expected to be higher than those compared to purely preventative maintenance

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[119] As discussed during stakeholder consultations during this study.

strategies (8-12% savings);[120] in practice, maintenance strategies, and therefore cost savings, are likely to lie between these two extremes.

Cost savings may also not be realised in practice for a variety of reasons. For example, advances in monitoring techniques may result in more intensive monitoring programmes which may balance out cost savings of the techniques themselves. Additionally, cost savings in subcontracted industries (such as drilling) may not be passed on to the consumer.

To illustrate the impact of uncertainties in selected cost reductions, sensitivities were run for these input parameters. The impact of varying the estimated cost reduction by ±50%[121] was tested for applications of additive manufacturing, composite pipelines, and AI for automation, predictive maintenance and virtual commissioning (Figure 3-11).

The levelised lifetime costs of capture plants (Figure 3-11a) are most sensitive to variations in predictive maintenance assumptions, due to the large proportion of cost associated with downtime. For storage sites, costs are equally sensitive to assumptions of automation and predictive maintenance (variation of ±2 percentage points in estimated cost reductions). The impact of uncertainty in the modelled impact of composite pipelines is lower than for AI applications but is close to ±1%. Conversely, the impact of uncertainties in the modelled impact of virtual commissioning on commissioning costs and process contingencies (due to increased confidence in processes), and additive manufacturing on capture costs are relatively small.

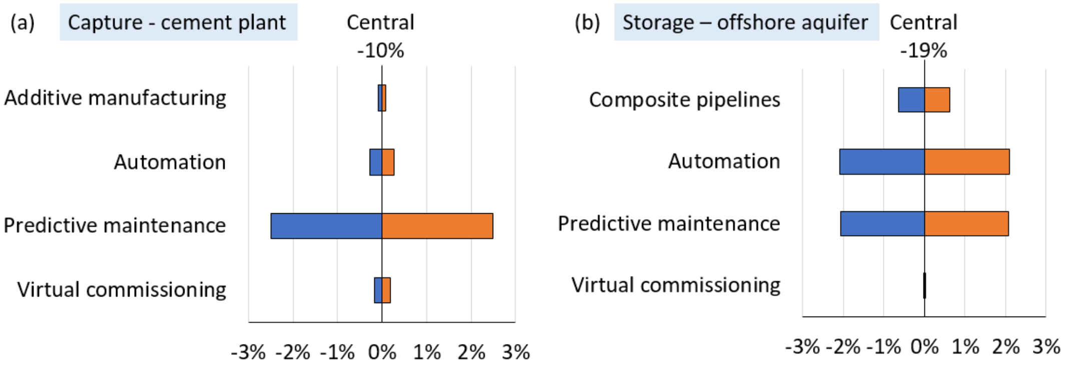

Figure 3-11 Effect of variation (±50%) in cost reduction potential (%) of selected digital and enabling technology applications on the overall reduction in lifetime cost of (a) a cement plant and (b) an offshore saline aquifer (both operating in 2040).[122]

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[120] https://www1.eere.energy.gov/femp/pdfs/OM_5.pdf

[121] For example, where 50% was used as the base case cost reduction, 25% and 75% were tested as sensitivities.

[122] Percentage change corresponds to change in estimated cost reductions in absolute percentage points (e.g. 8%-12% for capture plants)

3.2 Impacts of digital and enabling technologies on risks and challenges of CCS

3.2.1 Risks

Aside from cost, a number of technical, political and economic challenges are limiting large-scale deployment, including technical uncertainty of storage site performance, cross-chain coordination, plant integration challenges and the lack of market for stored carbon (see Section 6.7, page 68 for a full list of challenges considered). The main risks of relevance to applications of digital technologies are expected to be related to technical viability, although some political and financial barriers may also be addressed through technologies that increase confidence in projects. The main applications of emerging technologies expected to impact the risks and challenges in CCS are summarised in Table 3-3.

As outlined in Table 3-3, the potential impacts of all technology applications range from improved integration of capture technology into emitting plants to addressing potential bottlenecks in the supply chain and improving confidence in CO_2 storage security. Applications of digital innovations are expected to impact all of the identified risks, either through automation, enhanced analysis or virtual commissioning.

Although not listed in Table 3-3, challenges in **coordination of capture and storage projects** represent a major barrier to full chain CCS projects.[123] It is possible that this challenge may be impacted by digitalisation, but the scale of the overall impact and the technology application(s) with the most potential impact in this area are unclear. Key factors affecting project coordination are the interdependency of capture and storage site development, combined with the long development timescales of projects (3-4 years for storage site appraisal and 5-6 years for a capture plant).[124]

Improvements in storage site appraisal to reduce the barrier to taking FID is one area with potential impact. Additionally, innovations that help contribute to maximising the storage capacity of existing sites could reduce the need for new site development later in CCS deployment.

However, many of the risks and technological uncertainties are site-specific and unforeseen problems and difficulties are unlikely to be completely eliminated with advances in technology. This is particularly the case for storage, in which ground conditions and injectivity may still vary from predictions. Advances in nanomaterials are also at low TRL and their benefits in enhancement of storage may not be realised. Finally, market conditions may also play a role in supply chain risks which may not be fully addressed by technological advances.

3.2.2 Timescales

Although some digital and enabling technologies can reduce lead times for design and materials supply, the impact of the majority of technology deployment on individual project timescales is likely to be fairly small. Streamlined prototyping processes or digital simulations of facilities could reduce the time needed for plant design or FEED, however this impact is likely to be relatively minor.

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[123] *Challenges related to carbon transportation and storage – showstoppers for CCS?* (2017) J. Banks *et al.* for the Global CCS Institute
[124] S. Budinis *et al* (2018) Energy Strategy Reviews vol. 22, p 61-81 doi: 10.1016/j.esr.2018.08.003

Developments in seismic analysis or other sensing technologies could potentially accelerate storage appraisal; however, there is currently no precedent for this within other sectors since streamlining in the oil and gas sector has largely come from process changes rather than technological development.[125]

Overall, there is insufficient evidence to conclude that timescales for rollout of CCS would be significantly impacted by current developments in the technologies evaluated here. Small changes in individual elements may be accelerated to some degree but the components form part of a chain that requires coordination and, as described above, unforeseen problems may still occur. However, unforeseen disruptive developments cannot be ruled out and significant timescale reductions may be realised by future developments in CCS (see next section).

Given the importance of project coordination in CCS deployment, this is an area that should be investigated further.

Table 3-3 Summary of the potential impacts of emerging technologies on risks and challenges

Risk or challenge	Impact of digital enabling technologies
Capture site challenges footprint of capture plant, need for ducting, particularly where multiple vents are present	• **Virtual commissioning** in plant design may enable more efficient design and reduce integration issues. • Advances in **automation** may improve the efficiency of centralised capture facilities that receive flue gas from multiple sources. Centralised facilities could reduce the footprint required for single capture plants and remove the potential need for multiple capture plants for sites with multiple vents.
Industrial plant integration risks low opportunity for retrofit, downtime required for retrofit, increased operational complexity, impact on product quality, low familiarity of industrial sectors with gas separation	
Power plant integration risks Low operability of capture technology due to part-load limitations of compressor and slow startup/shutdown	• **AI-powered automation** can improve response times to external signals (such as grid demand or electricity price changes), and therefore may be able to improve operability of the capture plant.
Accessibility of global storage capacity (accessible pore volume) that is otherwise expected to be limited by reservoir pressurisation, particularly in lower quality reservoirs required beyond the first generation of storage projects	• The use of **nanomaterials** to enhance wetting could improve the accessible pore volume for CO_2; however, it is not clear whether this would mitigate the need for pressure management techniques • **Predictive analysis** may improve reservoir management to maximise storage in early, high quality storage sites
Proving storage capacity of a given site to a sufficient level to enable a financial investment decision (FID) to be taken	• Greater confidence through **intelligent modelling** and more accurate **sensing** techniques may reduce the risk in development.
Competition between CCS and oil and gas sector for experienced staff and drilling equipment necessary for	• **AI-powered automation**, such as drilling, could provide a solution whereby fewer expert operators are required, freeing up the supply chain

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[125] https://energynorthern.com/2018/09/10/in-the-race-to-first-oil-a-smart-drilling-approach-wins/

exploration, which could represent a bottleneck in the long term	- **AR remote assistance** may reduce the need for experienced operators to be present onsite
Potential for CO_2 release both through leakage from permanent storage sites and through accidental release (such as in the event of a pipeline disaster), representing an environmental risk, public perception risk and a financial risk through the uncapped liability of future storage leaks	- **Improved storage appraisal** through sensing techniques or modelling could reduce technical uncertainty and the financial risk of future leaks - **Better sensors and monitoring procedures** (e.g. **drones, robotics**) to detect leaks, improving confidence in infrastructure and in early detection of leaks from storage sites - **Enhanced CO_2 plume modelling** could reduce risk from pipeline disasters and aid design of safer onshore pipeline routes - **Improved surface wetting using nanomaterials** has been proposed to improve the effectiveness and security of storage

3.3 Impacts on future developments

A range of technological solutions aiming to reduce costs and address risks and challenges in CCS deployment are currently under development, including modular systems,[126] novel capture technologies[127] and direct air capture[128] (see Section 6.9, page 70 for further details). Many of these developments are still at low maturity (development or demonstration phase only) and therefore their impact and deployment in future CCS is highly uncertain. However, they have the potential to be disruptive within CCS and the impacts of digitalisation on these technologies as well as on the CCS chain as a whole may differ significantly from those estimated in this study.

For example, modular units aim to reduce costs and address issues of plant integration by providing standardised capture technology modules. Capex reductions of over 40% are estimated compared to conventional design, due to reductions across engineering, fabrication, installation and start-up costs.[129] These units potentially have a lower need for process control and automation, and experience fewer risks of plant integration and commissioning. As such, the overall cost reductions in these areas may also be lower than those estimated for standard FOAK and NOAK capture plants, process optimisation will likely still be of benefit. However, because the components of modular systems are prefabricated and standardised, they are particularly suited to production by additive manufacturing, meaning that the benefits of AM for these systems could be higher.

Alternative capture technologies such as metal organic frameworks (MOFs) and membrane separation technologies have entirely different fabrication and deposition procedures, energy requirements and component requirements to solvent-based systems; therefore, the impact of digital technologies on these systems cannot be predicted. However, MOFs may

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[126] https://akersolutions.com/news/news-archive/2019/aker-solutions-signs-carbon-capture-contract-with-twence-in-the-netherlands/
[127] K. Sumida *et al.* (2012) Chemical Reviews vol 112, p. 724-781 doi: 10.1021/cr2003272
[128] *Greenhouse Gas Removal* (2018) Royal Society and Royal Academy of Engineering
[129] https://akersolutions.com/news/news-archive/2019/aker-solutions-signs-carbon-capture-contract-with-twence-in-the-netherlands/

benefit greatly in the research and development phase, through use of deep learning to predict behaviour and reduce the material discovery timescale dramatically. Membranes for CO_2 separation may benefit in future from integration of advanced materials such as graphene, which is currently under investigation in the water desalination sector.[130,131]

Since future technological solutions for CCS will develop simultaneously with developments in digital technologies, it is anticipated that many may contribute to or be incorporated into these technologies during design. As such, the impact of digitalisation on these technologies is likely complex and difficult to separate from the benefits to CCS realised by the technologies themselves.

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[130] H. Qui *et al.* (2019) Advanced Materials vol 31, p. 1803772
https://doi.org/10.1002/adma.201803772

[131] https://www.ku.ac.ae/advanced-materials-explored-for-energy-efficient-desalination/

4 Implications of emerging technologies for global CCS deployment

4.1 Cost savings in a global context

The projected cost reductions modelled in Chapter 3 reflects the benefit that digital technologies could deliver at the individual project level. To put these savings into context of the required scale of global CCS deployment, the impacts were mapped to international CCS deployment projections.

Methodology

The approach is summarised in Figure 4-1, and detailed assumptions are given in Section 6.5 (page 64). The IEA 2°C Scenario (2DS) was used as the basis for the projections,[5] with the projected CO_2 capture rate providing a proxy for project deployment rate (Figure 4-2). The capture archetypes were then mapped to the relevant deployment projections by sector (Figure 4-2 (b)) to derive the expected global investment savings.

A regional scaling factor was applied to the costs both with and without emerging technologies to broadly adjust for differences in CCS costs across regions (see Section 6.5 for details). For simplicity, investments in transport and storage (T&S) networks were included as a fixed cost ($11/tCO2), in line with literature T&S fees.[105] The proportions of the T&S cost attributed to transport and storage, respectively, were assumed to be in-line with the relative costs of the archetypes used in this study (35% transport, 65% storage).

The derived cost savings relate to savings over the lifetime of projects deployed in each year – i.e. the projected cumulative cost savings in 2040 refer to the expected savings for all projects deployed up to and including 2040, over the lifetime of those projects. Capture project lifetimes of 20 years were assumed, in line with the assumptions in Chapter 2.

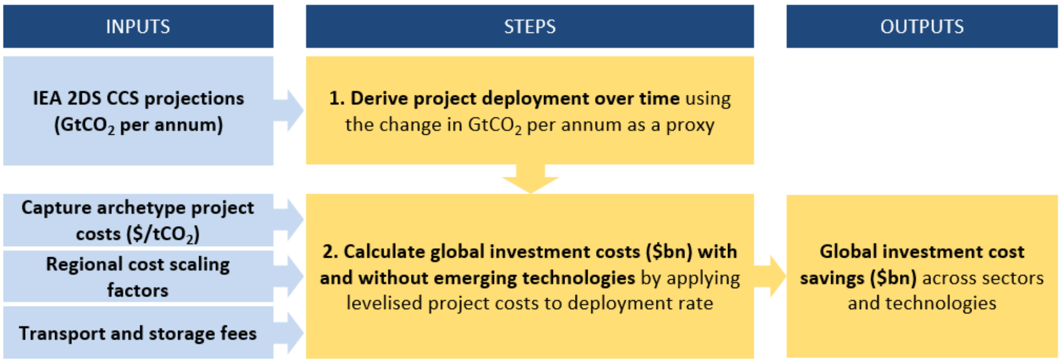

Figure 4-1 Summary of approach to modelling global cost savings due to deployment of emerging technologies in CCS projects

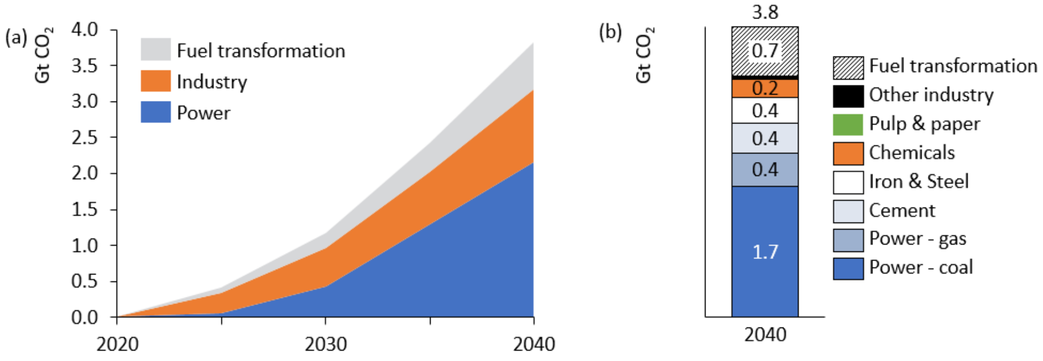

Figure 4-2 Projected CO_2 captured by sector (a) over all years and (b) in 2040[132]

Projected global cost savings

Following the deployment trajectory assumed in the 2DS, total cumulative global savings of close to $200bn (10%) in lifetime costs of projects deployed up to and including 2040 are possible (Figure 4-3). Of this:

- 8% is estimated to be saved in capital expenditure
- 27% is estimated to be saved in operational costs
- 47% of savings are due to carbon costs of downtime and leakage
- 13% is expected to be saved in T&S, of which 96% is saved in storage projects

For capture plants, the largest savings are in the power CCS sector, accounting for 77% of the expected savings in capex ($13bn), 76% of savings opex ($41bn) and 61% of carbon costs (downtime and leakage).

The industrial sector accounts for 20% of savings, with close to 90% of these savings in the Cement and Iron & Steel sectors (44% and 43%, respectively; Figure 4-3(b)). Although chemical industries account for close to a quarter of industrial CO_2 captured, only 7% of investment savings are in this sector; this reflects the already relatively low cost of CCS in this sector, due to the high proportion of industries that produce pure CO_2 streams (such as ammonia production).

More than half of the projected cost savings are due to applications of digital innovations (Figure 4-4). Additive manufacturing accounts for half of the savings in capex, and 9% of savings overall. In line with the findings for individual projects, most of the savings from applications of robotics, drones and autonomous systems, and novel sensors are in T&S, with these technologies accounting for 6% and 4% of overall savings, respectively. Advanced materials contribute to 6% of T&S savings, but only 1% of overall savings.

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[132] Derived from data in *Energy Technology Perspectives* (2017) IEA

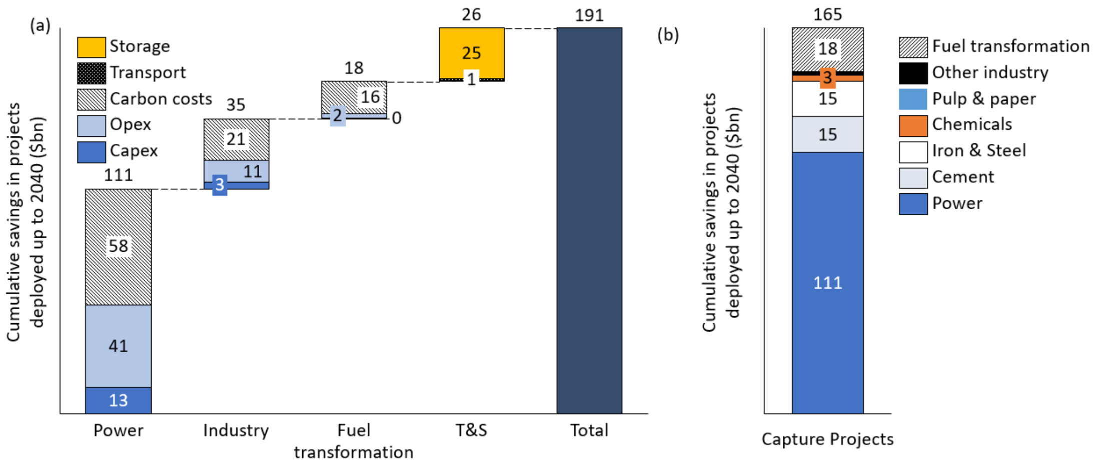

Figure 4-3 Cumulative savings across the CCS chain for projects deployed up to 2040, based on deployment projections in the IEA 2 Degree Scenario: (a) Breakdown by broad sector, (b) breakdown of capture projects by sector.

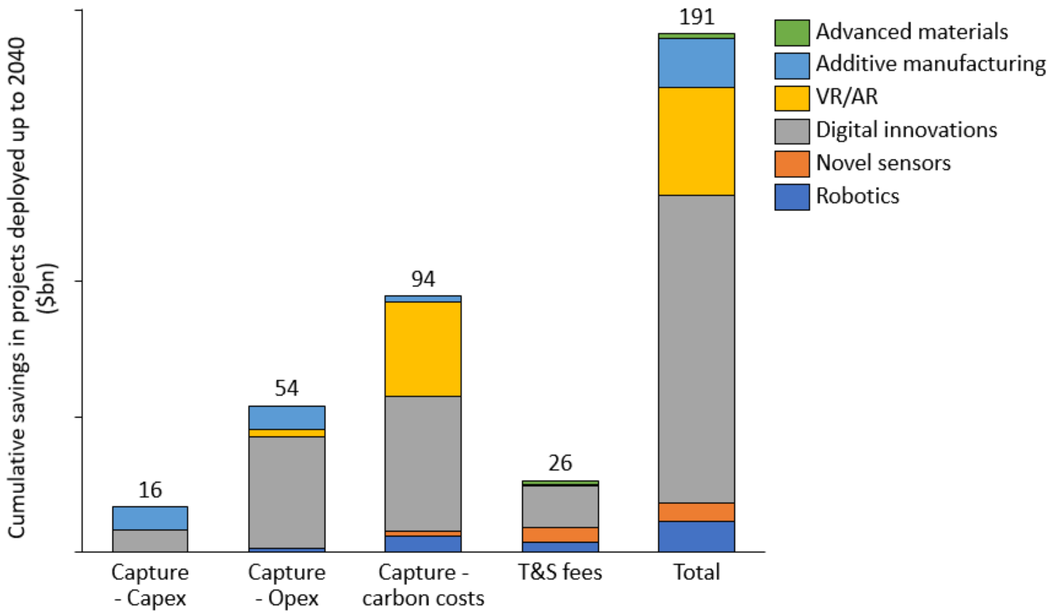

Figure 4-4 Distribution of global cost savings by emerging technology group.

4.2 Further implications for global deployment

The advent of these emerging technologies may have additional impacts on the global deployment scenarios, either through global integration, or the cost competitiveness of CCS.

Data Exchange

Digital technologies can allow opportunities to enhance the learnings associated with the deployment of CCS globally. Data exchange platforms are already being put in place, for example in the CO_2 DataShare project[133] or the public availability of MMV and performance data from the Quest project.[134] The UK Oil and Gas Authority has also recently established a National Data Repository for reservoir development data sharing, which is also expected to benefit CCS projects.[135] Advancements in AI and machine learning can enable these repositories to be fully utilised, accelerating learning rates for projects.

In addition to communicating learnings from CCS projects, efficient data sharing can occur between actors in different parts of the chain, helping to increase the efficiency of operations. If the owners of the capture plant can communicate with the operators of both transport and storage infrastructure and vice versa (for example, real-time reporting of CO_2 purity fluctuations) this can enable better operation of the available infrastructure. Since large-scale networks do not currently exist, there is both uncertainty of the way that these networks will operate but also opportunity to integrate digital technologies from the beginning. Procedures need to be implemented on a case by case basis, learning from the operation of projects within CCS and initiatives in related industries, such as the natural gas supply chain.

Scale of Global Deployment and Cost Competitiveness

Within this study, cost reductions have been considered in the context of improvements within CCS, rather than in the wider context of the competitiveness of CCS with other renewable technologies. Future energy scenarios require a mix of renewable technologies, and the benefits of digitalisation are likely applicable across the energy sector. The relative impact of digitalisation on each renewable energy solution is expected to be complex; however, there may be an effect on competitiveness with other renewable technologies resulting in either increased or decreased deployment of CCS.

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[133] https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2570034
[134] https://open.alberta.ca/dataset?tags=Quest+Carbon+Capture+and+Storage+project
[135] https://www.ogauthority.co.uk/data-centre/national-data-repository-ndr/

5 Conclusions and recommendations

5.1 Key messages

- **There are a wide range of relevant applications** for digital and enabling technologies across the CCS chain, with the potential to reduce costs and address risks and challenges to deployment.
- **The benefits of these technologies are largely transferrable from related sectors** to CCS, with CCS-specific applications of additive manufacturing, machine learning and nanomaterials for enhanced CO_2 storage already under development (although currently at low maturity).
- Across the CCS chain, **applications of AI and IoT** in predictive maintenance and automation **deliver the greatest reductions in project costs**, through reduced labour and maintenance costs, and reduced facility downtime.
- In line with current technology maturity and the development timescales of CCS, **significant savings are only expected to be realised from 2030.**
- **The greatest absolute ($/t$CO_2$) savings are projected to be in capture whereas the greatest relative (%) savings are in storage.**
- On a global scale, **cumulative investment savings of almost $200bn** in the lifetime costs of CCS projects deployed through to 2040 are possible, representing a saving of 10% of the counterfactual investment cost.
- The impact of digital and enabling technologies on risks and challenges to deployment are primarily expected to be through improved efficiency of integration and flexibility of operation of CCS plants, and through reduced technical uncertainty.
- Applications of digital and enabling technologies that reduce technical uncertainty are expected to improve confidence for project developers, policy makers and financial institutions, facilitating project deployment.
- Digital and enabling technologies are also subject to risks and challenges to their uptake and utilisation. The impacts of these risks must be minimised to facilitate uptake and realise the benefits of these technologies within CCS.
- While many of the applications of digital and enabling technologies can reduce timescales of design and supply of equipment, the overall impact of these technologies on project development timescales is expected to be relatively small.
- It is likely that advances in subsurface sensing and AI could improve development timescales in future, helping to address issues of project coordination; however, there is currently no precedent for this in related sectors.
- Digitalisation has additional key benefits of greater knowledge accumulation and sharing, that could serve to accelerate learning within the sector.

5.2 Recommendations for further work

This study has provided a high-level assessment of the potential impacts of digitalisation on CCS costs and risks and the implications of these impacts for global deployment. Although this study has highlighted the technologies that are expected to have high impacts, additional research is required before the next steps in development of these technologies for CCS can be identified. In the near-term, these studies should focus on addressing the uncertainties associated with cost reduction projections, as well as the wider implications of digital and enabling technology uptake.

Recommendations to improve confidence in cost and risk assessments

Although the analysis presented here was based on the best available data, there is significant uncertainty inherent in the cost reduction projections. Although both the scale of the projected cost reductions and the relative impact of each the technologies are likely to be reflective of what can feasibly be achieved,[136] the absolute cost savings for each element of the chain are highly uncertain. Suggestions of further work to address this uncertainty include:

- **More detailed assessment of the likely impact of integrating digital and enabling technologies into real CCS projects**. This may include engagement with project developers and operators to enable better understanding of:
    - cost allocations within projects, particularly regarding the relative costs of pipelines within injection facilities and the opportunities for replacement by more cost-effective alternatives;
    - the degree of automation expected to already be present in typical projects and the opportunity for improvement across capture, transport and storage;
    - the typical maintenance behaviour, and the opportunity for cost reductions through predictive maintenance;
    - the degree to which virtual commissioning could reduce plant integration challenges and process contingencies;
    - risk perception and decision-making factors affecting inclusion of digital and enabling technologies in projects;
    - **t**he potential impacts of failure of digital systems and potential mitigation strategies that could be put in place.
- **More in-depth assessment of the potential applications of each technology group** within CCS to enable more confident assessment of the level of impact expected. This is particularly relevant for additive manufacturing where the benefits are case-specific and difficult to generalise. However, it would also be of benefit to explore the likelihood of technology development in areas that can reduce project timescales and address challenges of project coordination.

Recommendations to assess the wider implications of digital and enabling technology uptake

The analysis presented here represents a ‘best case’ scenario of digital and enabling technology uptake, in which all technologies are assumed to be implemented across all projects globally. Further work to understand the wider implications for uptake could include:

- **Assessment of regional factors affecting global uptake and impacts.** This may include a more detailed assessment of the local variation of project costs and cost reduction potential, as well as an assessment of local political and social barriers and political readiness for digital technology uptake.

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[136] As discussed with stakeholders during this study

- **Assessment of digitalisation of CCS within the context of the wider energy sector.** This study has considered CCS in isolation but, in practice, CCS will be integrated with the emitting plant which in turn will be integrated into a wider energy or supply chain network. This assessment could include understanding the drivers that each part of the network faces and how they shape the impact of digitalisation across the network, including on CCS.

Long-term research objectives

Once further evidence has been gathered, as recommended above, future work in this area can include activities such as **defining a detailed roadmap** for the development of digital technologies in CCS, **identification of incentives or targeted funding** requirements for acceleration of digital technology uptake, and **encouraging collaboration** between key stakeholders to ensure uptake.

6 Appendix

6.1 Assumptions for applications of digital and enabling technologies across the CCS chain

Robotics, drones and autonomous systems

Asset inspection and monitoring was assumed to apply across the CCS chain for a range of applications:

- For **Capture** this represents inspection of assets at height, such as external pipelines and solvent columns
- For **Pipelines** this represents replacement of incumbent systems for both internal inspection of pipelines (pigging) and pipeline route inspection – replacing a helicopter survey onshore and a remotely operated underwater vehicle (ROV) or diver inspection offshore
- For **Shipping** this includes tanker inspection for class surveys, replacing visual inspection in a dry dock survey
- For **Storage** this includes both offshore asset inspection and post-closure monitoring of subsea assets after decommissioning. Storage sites are assumed to be unmanned installations; therefore asset inspection is primarily considered as a replacement for regular site visits. Post-closure monitoring of subsea assets following decommissioning is not typically considered in cost models since it is assumed that structures are fully removed; however, with a low-cost monitoring option available, subsea structures can be left in place, reducing the cost of decommissioning.

Remote repair is assumed to primarily apply to pipelines, with repair of offshore storage sites incorporated into asset inspection cost reductions.

For all robotics applications, the development timeframe assumes primarily remotely operated systems in 2025, moving towards fully autonomous systems by 2040. Applications and advances in autonomous underwater vehicles are assumed to lag behind those of aerial vehicles; therefore applications for offshore pipelines are assumed to develop later (from 2030 onwards).

Sensors

Subsurface sensing is assumed to be applicable to seismic surveying during storage site appraisal, ongoing monitoring, measurement, and verification (MMV) during operation and for post-closure monitoring. In each case, cost reductions were based on the assumption that some or all of the conventional surveys could be replaced from 2030.

Corrosion monitoring represents replacement of visual inspection by an ROV or diver. Since these systems can be incorporated into IoT and AI applications in future, improvements in cost reductions beyond 2030 are assumed to primarily be captured by those for digital innovations.

CO_2 detection relates to the augmentation of visual inspection and flow sensing (such as SCADA for pipelines) by sensor networks deployed at critical equipment (capture plant and storage sites) and pipelines.

Digital innovations

Automation and optimisation and **Predictive maintenance** are assumed to be applicable across the chain. Improvements in the costs of maintenance are based on moving from typical operations in the counterfactual case (a mix of preventative, reactive and conditional monitoring) to best practice (fully predictive). For storage, reduction in the costs of drilling due to automation or AI-powered solutions in future are also considered.

Advanced analysis relates to improved modelling and assessment of site survey data to improve decision-making and reduce site appraisal time.

Predictive analysis considers improvements in reservoir management to increase storage capacity during the lifetime of the site; however, this application was not included in the cost modelling.

Virtual commissioning is assumed to be primarily applicable to capture plants, where plant integration and capture technology optimisation are significant challenges. However, applications in injection facility development are also considered in the analysis. The primary impacts are considered to be in the costs of commissioning but reductions in process contingency due to improved confidence during design, construction and commissioning are also considered.

The impacts of **distributed ledgers** are only considered for capture plants since the largest administration burden of compliance with carbon credits or certification is assumed to lie with the emitter. However, in practice, verification of storage will benefit the whole CCS chain.

Additive manufacturing

Enhanced design and performance is primarily considered applicable for improvements in capture technology that are already under development, as well as in equipment such as compressor components and turbines.

Spare part printing is considered primarily applicable for capture plants, storage sites and liquefaction plants in the shipping chain.

Advanced materials

Only the two applications described in Chapter 2 are considered, with both applicable in storage. **Enhanced CO_2 storage** through nanomaterial-enhanced subsurface wetting is not considered in the cost modelling, although an increase in the storage capacity and/or the lifetime of the site would reduce the overall levelised lifetime costs.

6.2 Counterfactual costs for CCS

General considerations

Table 6-1 Assumed project timescales used in the cost modelling

	Assumed duration (years)			
Stage	**Capture**	**Pipeline transport**	**Shipping**	**Storage**
Pre-construction	5	6	5	4
Construction	4	2	4	3
Operation	20	20	20	20
Post-closure monitoring	—	—	—	20

Capture

- Capital and operational costs for the power and industrial sectors were taken from the 2017 Global CCS Institute cost report to ensure a common reference base for the costs (US Midwest location, 2015 price year); project operational parameters are summarised in Table 6-2 and Table 6-3.

- Reference cases are first of a kind (FOAK), assumed to be using mature capture technologies where applicable (first generation amines) and including costs of compression.

- For power CCS, costs are based on new build plants with reference to the costs and emissions of a plant without CCS with an equivalent net power output.

- Fuel costs were based on US projections[137], adjusted to $2015 price year using the relative price index.

- Decommissioning costs, site-specific costs (cost of connection) and taxes were not included.

- For industrial CCS, fuel requirements for compression and capture were calculated using an in-house model.[138]

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[137] US Energy Information Administration https://www.eia.gov/analysis/projection-data.php

[138] *The costs of Carbon Capture and Storage (CCS) for UK industry* (2013) Element Energy for UK Government

Table 6-2 Operational parameters used for Power CCS plants

	Reference case assumptions (with CCS)	
Power CCS plant type	**PC supercritical**	**NGCC**
Net power output (MW)	550	550
Net plant efficiency (%)	32.5	45.7
CO_2 captured ($MtCO_2$/y)	3.6	1.5
Load factor	85%	85%

Table 6-3 Operational parameters used for Industrial CCS plants

	Reference case assumptions (with CCS)				
Industrial CCS plant type	**Cement**	**Iron & Steel**	**Natural gas processing**	**Ammonia**	**Biomass-to-ethanol**
Emissions intensity of product (tCO_2/t)	0.83	2	0.19	0.57	1.05
CO_2 captured ($MtCO_2$/y)	0.29	0.71	1.0	0.19	1.0
CO_2 stream purity (%)	19%	22%	100%	100%	100%

Transport

Pipelines

- Both offshore and onshore pipeline costs are based on full scale projects with a flow rate of 10 Mtpa and a representative pipeline length of 180 km
- Onshore pipelines are assumed to have an inlet pressure of 10 MPa with a pressure drop of 2 MPa
- Offshore pipelines are assumed to have an inlet pressure of 25 MPa with a pressure drop of 15 MPa
- Offshore pipeline costs include the cost of booster compression to meet the increased pressure from onshore to offshore transport
- Pipeline diameters were set to 24” for onshore pipelines and 20” for offshore pipelines

Shipping

- Assumptions for the reference case are based on cost-effective transport conditions, as set out in Table 6-4[139]

Table 6-4 CO_2 shipping operational assumptions

Assumptions	
Unloading option	Onshore
Flow rate	1 Mtpa
Distance	600 km
Initial CO_2 condition	Pre-pressurised
Transport CO_2 condition	7 barg
Ship size	10 $ktCO_2$
Ship fuel	LNG
Ship fuel price	Central
Liquefaction fuel price	Central
Lifetime	20 years

Storage

- Storage costs for offshore saline aquiferss were based on the average costs of storage sites analysed by the UK Storage Appraisal Project, calculated[140] based on the following assumptions:
  - 5 $MtCO_2$/yr flow rate
  - 20 years of injection
  - 10% Injection well redundancy
- Costs for onshore saline aquifers were calculated by scaling offshore aquifer cost components according to the previously reported relative costs for onshore and offshore saline aquifers.[141]

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[139] Shipping CO_2 – UK Cost Estimation Study (2018)

[140] Element Energy in-house brine production cost-benefit analysis tool, developed for the Energy Technologies Institute

[141] *The costs of CO_2 storage* (2011) Zero Emissions Platform

6.3 Assumptions for detailed counterfactual cost components

Aside from those stated below, the relevant cost components were already included in the counterfactual cost from the data source.

Capture

Capex components

Capture technology	**For Power CCS:** capture technology was assumed to be 70% of costs (excluding Owner's costs)[142, 143] **For industrial CCS:** calculated by subtracting the scaled cost of an ammonia plant (scaled using the relative capture capacities and a scaling factor of 0.66) from the total costs
Commissioning	3% of total plant cost[144, 145]
Staff training prior to commissioning	3 months of operating labour costs[146]
Owner's costs - Strategic spares	2% of capex[144]

Opex components

Opex - maintenance labour	20% of all staff costs[147]
Opex - maintenance materials	All fixed materials costs assumed to be associated with spare parts and maintenance
Staff training ongoing	1% of labour cost[146]

Pipelines

Capex components

Pre-FID: Pipeline route survey (design)	Based on cost of helicopter survey at $3.5/km[148] (onshore) and ROV survey at $5,000/day (offshore)[149]

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[142] *Kingsnorth Carbon Capture and Storage Project: Post-FEED Project Cost Estimates* (2011) EON
[143] *CCUS Technical Advisory Report on Assumptions* (2018) Uniper
[144] *UK Carbon Capture and Storage Demonstration Competition FEED Close Out Report* (2011) ScottishPower CCS Consortium
[145] *Peterhead CCS Project Cost Estimate Report* (2011) Shell
[146] Based on the EU Labour Cost Survey, available at https://ec.europa.eu/eurostat/statistics-explained/index.php/Labour_cost_structural_statistics_-_levels#Structure_of_labour_costs
[147] *Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology Benchmarking State-of-the-art and Next Generation Technologies* (2018) BEIS
[148] *Automatic pipeline surveillance air-vehicle* (2016) H. Alqaan Available at: https://dspace.lib.cranfield.ac.uk/handle/1826/9876
[149] C. Mai *et al.* (2016) IEEE International Conference on Underwater System Technology: Theory and Applications (USYS) doi: 10.1109/USYS.2016.7893928

Opex components

Pipeline Pigging	$1.4m per pig run, with run every 5 years[150]
Pipeline visual inspection	Onshore based on helicopter survey carried out 26 times per year; Offshore based on ROV, once per year
Pipeline repair	30% of opex[145]
Pipeline labour opex	33% of opex[145]

Shipping

Capex components

Spare parts (onshore infrastructure)	2% of capex, as for capture

Opex components

Shipping - Ship inspection opex	5% of total opex[151] (including fuel)
Shipping - Ship maintenance opex	5% of total opex (including fuel)[152]
Shipping - Ship crew	65% of remaining costs [152]

Storage

Capex components

Offshore	
Seismic appraisal - labour	50% of appraisal cost due to labour[153]
Injection facility construction capex	Assume 30% is due to pipelines, based on half proportional cost of subsea assets[154]
Injection facility spare parts	0%[144]
Injection facility staff training	3 months of labour cost, as for capture
Injection well capex	From source data
Monitoring wells	Assume no monitoring wells for offshore[107]
Decomissioning Post-closure monitoring of assets	14% due site remediation, subsea structure and ongoing monitoring[155]

Opex components

Injection facility maintenance opex	27% of opex[144]

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[150] *CO_2 Pipeline Infrastructure* (2013) IEAGHG
[151] Brevik Engineering, personal communication
[152] https://clarksonsresearch.wordpress.com/tag/opex/
[153] Innoseis, personal communication
[154] E. Calixto in *Gas and Oil Reliability Engineering (2nd Edition)* (2016)
[155] *UKCS Decommissioning* (2018) Oil and Gas Authority

Injection facility labour opex	20% opex[144]
Injection well maintenance	27% of opex[144]
Injection well labour opex	20% of opex[144]
Operational MMV	Half the cost of a full seismic survey[107]

6.4 Modelled cost reductions due to emerging and enabling technologies

Capture

			Estimated cost reduction		
Technology group	**Application**	**Component impacted**	**2025**	**2030**	**2040**
Robotics, drones and autonomous systems	**Asset inspection**	• Maintenance labour costs • Plant downtime	1% 1%	5% 3%	10% 5%
Novel sensors	**CO_2 detection**	• CO_2 leakage rate	10%	15%	20%
Digital innovations	**Blockchain** for verification of CO_2 capture and storage	• Administration costs of CO_2 reporting	—	33%	33%
	Automation of capture processes	• Operational labour costs	—	25%	50%
	Predictive maintenance	• Plant downtime • Maintenance labour costs	—	30% 15%	40% 30%
	Virtual commissioning	• Commissioning costs • Construction costs • Process contingency	—	10% 1% 10%	15% 3% 15%
VR/AR	**Enhanced maintenance**	• Maintenance labour costs	10%	10%	10%
	Enhanced training	• Staff training costs	20%	30%	40%

Additive manufacturing	**Improved efficiency and durability** through improved design, either from bespoke (novel) components or from rapid prototyping e.g. for compression or for steam turbine efficiency	• Compressor energy consumption	1%	1%[a]	2%[a]
		• Capture energy consumption		1%	2%
		• Maintenance materials cost		2%	5%
		• Maintenance labour cost		2%	5%
		• Capture materials and construction cost		1%	3%
	Printing of spare parts	• Sunk cost of critical spares	20%	50%	75%
		• Plant downtime		1%	2%

[a] Corresponding to a 5% and 10% increase in compressor efficiency

[b] Based on a cement plant operating in 2040, with 20 year lifetime and discount rate of 3.5%

Pipeline transport

			Estimated cost reduction (onshore/offshore where differs)		
Technology group	**Application**	**Component impacted**	**2025**	**2030**	**2040**
Robotics, drones and autonomous systems	**Pipeline route survey** replacing visual inspection by helicopter (onshore) or ROV/diver (offshore)	• Pipeline route monitoring cost • Pipeline survey costs during design	50%/0% 50%/0%	50% 50%	85% 85%
	Internal pipeline inspection replacing intelligent pig runs and allowing inspection of previously unpiggable pipelines	• Maintenance costs due to pigging		50%	75%
	Rapid leak repair by robots and, later, drones	• Pipeline repair cost • CO_2 leakage	10%[2]/0% 0%	30%/10% 20%	50% 20%
Novel sensors	**CO_2 leak detection** along pipeline length	• CO_2 leakage	10%	15%	20%
Digital innovations	**Automation of pipeline pressure**	• Operational labour costs		25%	50%
	Predictive maintenance	• Maintenance costs		15%	30%

Shipping

			Estimated cost reduction		
Technology group	**Application**	**Component impacted**	**2025**	**2030**	**2040**
Robotics, drones and autonomous systems	**Ship class inspections** replacing traditional (manual) surveys	Ship dry-dock costs		20%	25%
Digital innovations	**Autonomous and semi-autonomous ships** unmanned or minimally manned with onshore operational team	Ship opex Ship capex			30% +10%[a]
Additive manufacturing	**Rapid printing of spares** for onshore (at port) assets: liquefaction, loading and unloading	Sunk costs of critical spares	20%	50%	75%

[a] Increase in capex assumed based on *Business case of the unmanned vessel* (2015) presented at the MUNIN Final Event, Hamburg http://www.unmanned-ship.org/munin/wp-content/uploads/2015/06/MUNIN-Final-Event-C-1c-CML-Business-case-of-the-unmanned-vessel.pdf

Storage

			Assumed cost reduction (onshore/offshore where differs)		
Technology group	**Application**	**Component impacted**	**2025**	**2030**	**2040**
Robotics, drones and autonomous systems	**Remote facility inspection**	• Injection facility maintenance costs • Storage downtime	25%	50% 10%	75% 15%
	Post-closure monitoring of assets	• Injection facility decommissioning cost		0%/15%	0%/15%
Novel sensors	**Seismic sensing**	• Seismic appraisal cost • Operational monitoring cost • Post-closure monitoring cost	20% 40%[a]	20% 30% 40%	30% 40% 40%
	Corrosion sensing	• Injection facility maintenance cost • Downtime		5%/10% 5%	5%/10% 5%
	CO_2 leak detection	• CO_2 leakage rate • Liability transfer fee	10% 20%[2]	15% 20%	20% 20%
Digital innovations	**Automation of injection processes**	• Injection facility and well operational cost		25%	50%

	Predictive maintenance	• Injection facility and well maintenance costs • Downtime		15% 30%	30% 40%
	Intelligent analysis of seismic data	• Seismic appraisal cost		10%	15%
	Virtual commissioning of injection facility	• Injection facility construction capex • Injection facility contingency		1% 3%	1% 3%
VR/AR	**Enhanced remote inspection**	• Injection facility maintenance cost	10%	10%	10%
Additive manufacturing	**Rapid printing of spares**	• Sunk costs of critical spares	20%	50%	75%
Advanced materials	**Composite pipelines** for risers and flowlines to reservoir	• Injection facility capex • Injection well capex • Injection facility and injection well capex and maintenance opex		10% 10% 10%	20% 20% 20%

6.5 Methodology for global cost reduction estimates

Assumptions:

- Coal accounts for 80% of CO_2 captured from power CCS[156]
- Most of the CCUS deployment in the fuel transformation sector is linked to the production of biodiesel or bioethanol[156]
- Ammonia production accounts for 75% of CO_2 captured from the chemicals sector[157] (IEA role of CO_2 storage)
- The costs of CCS for other industrial sectors were approximated as weighted averages of similar industry archetypes
- Transport and storage costs were represented as a fixed cost of $11/t$CO_2$ for all years: this is used to capture the costs of global deployment of pipeline and shipping infrastructure and storage sites of sufficient capacity; used since it is difficult to estimate global pipeline lengths and locations and to capture complexities of storage capacity and site lifetimes
- Transport was assumed to account for 35% of T&S fee based on our archetypes
- Storage was assumed to be equally distributed between onshore and offshore sites
- Capture plants were assumed to have a lifetime of 20 years with new projects deployed in 2040 to replace those deployed in 2020

Regional aspects:

A regional cost factor was applied to capture costs only, to reflect differences in project costs:

In 2040:	**Proportion of CO_2 captured**			
Power CCS: [156]	**EU**	**China**	**US**	**Rest of the World**
Coal	3%	73%	5%	19%
Gas	5%	20%	62%	13%
Industrial CCS[157]	7%	27%	14%[158]	52%

Regional cost scaling factors:[159]

	PC Supercritical	**IGCC**	**NGCC**	**I&S**	**Cement**	**NG**	**Fertiliser**	**Bioethanol**
Average cost factors								
US	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Europe	1.29	1.21	1.29	1.20	1.28	1.23	1.23	1.23
China	0.81	0.84	1.11	0.96	1.04	1.13	1.09	1.13
ROW	1.19	1.24	1.18	1.11	1.11	1.07	1.08	1.13

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[156] *World Energy Outlook* (2018) IEA
[157] *Exploring Clean Energy Pathways: The role of CO_2 storage* (2019) IEA
[158] Value for North America, rather than US-specifically
[159] Derived from the relative cost of CCS across regions as detailed in *Global Costs of Carbon Capture and Storage* (2017) Global CCS Institute

6.6 Impact of emerging technologies across the CCS chain

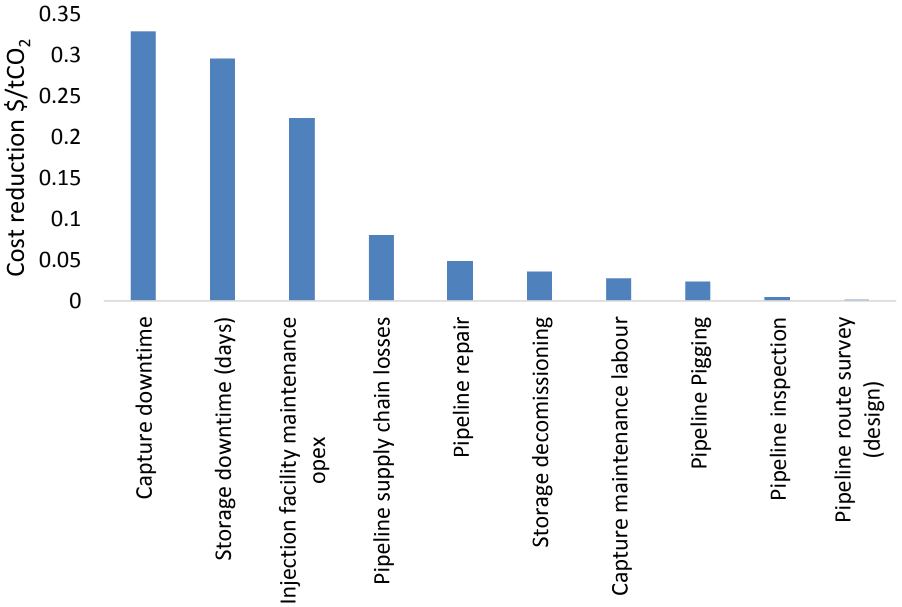

Figure 6-1 - Impact of robotics, drones and autonomous systems across the CCS chain

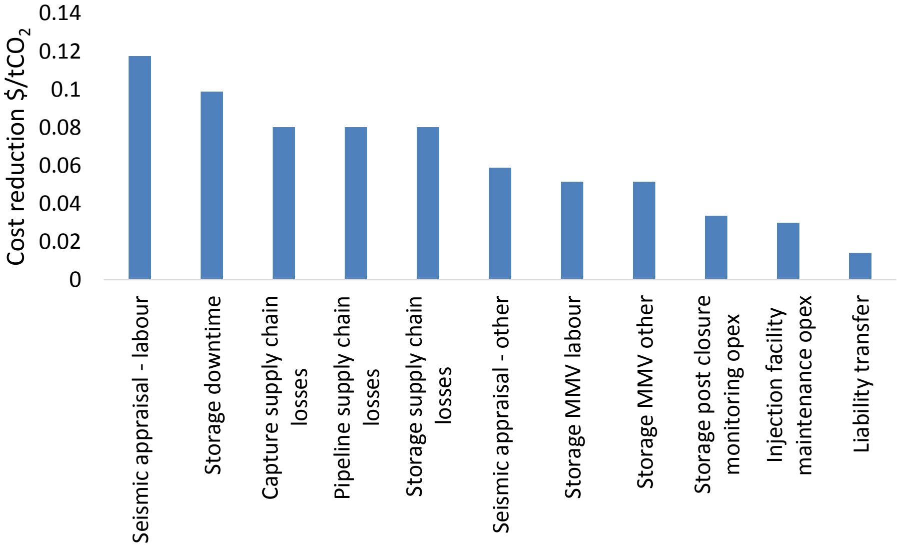

Figure 6-2 Impact of novel sensors across the CCS chain

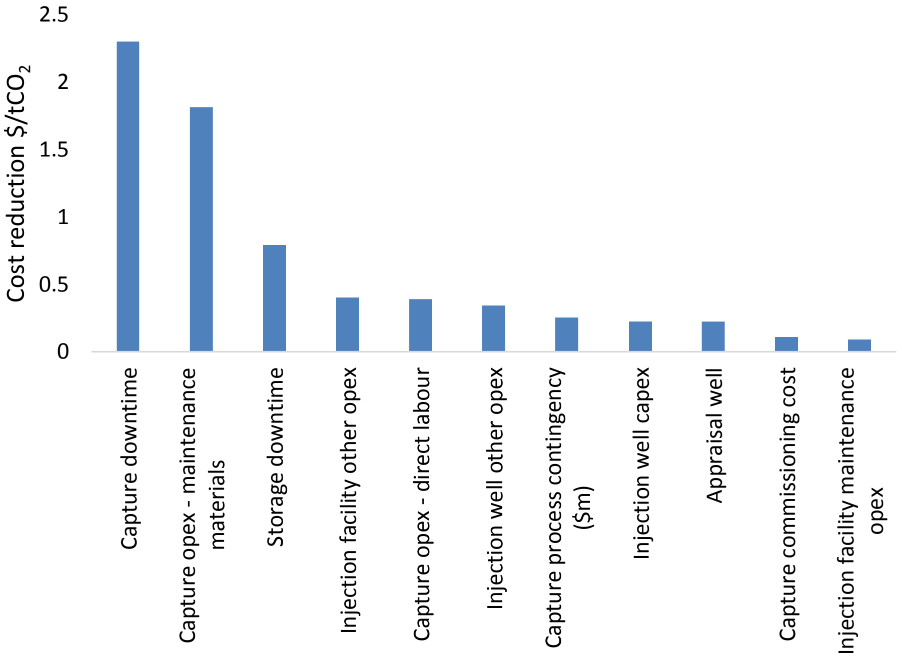

Figure 6-3 Impact of digital innovations across the CCS chain

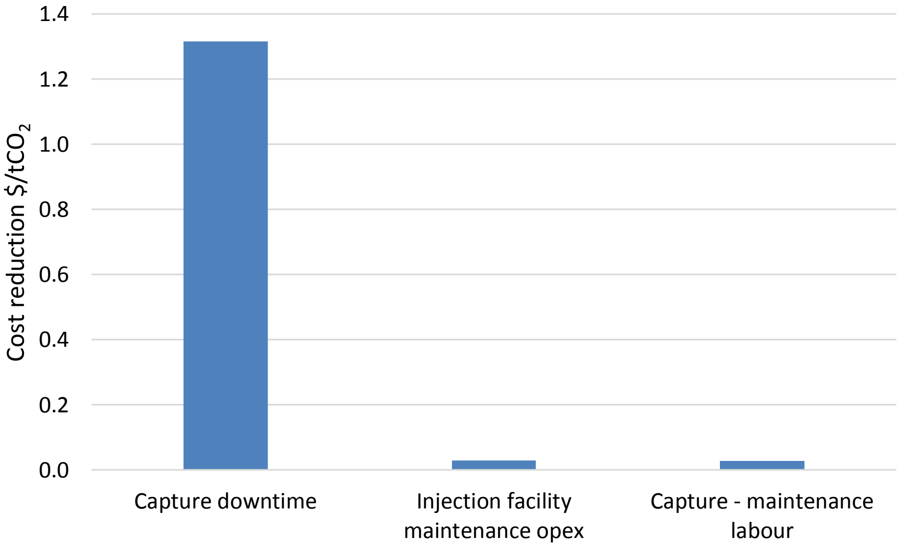

Figure 6-4 Impact of VR/AR across the CCS chain

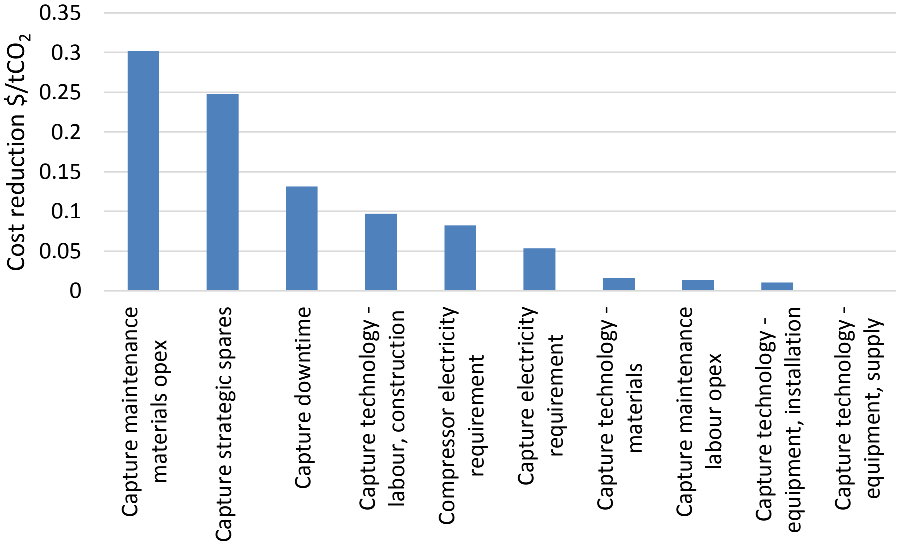

Figure 6-5 Impact of Additive manufacturing across the CCS chain

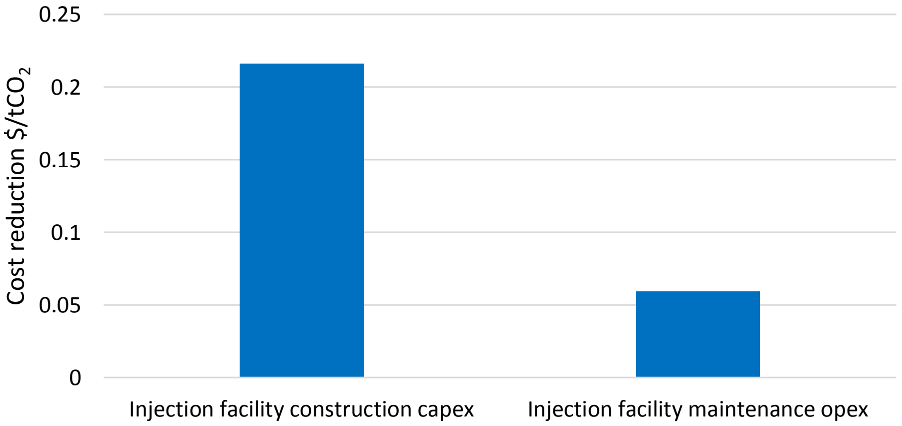

Figure 6-6 Impact of Advanced materials across the CCS chain

6.7 Effect of discount rate on projected cost reductions

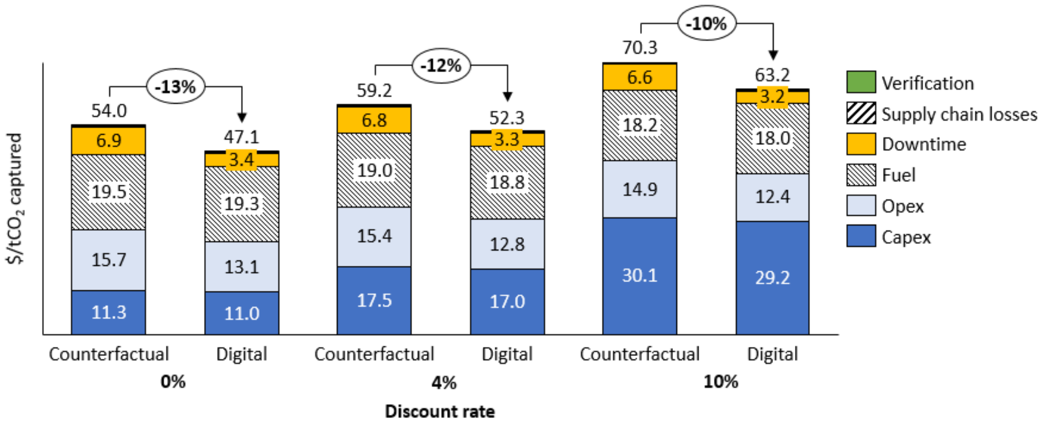

Figure 6-7 Effect of applied discount rate on projected reductions in levelised lifetime cost for a cement plant operating in 2040

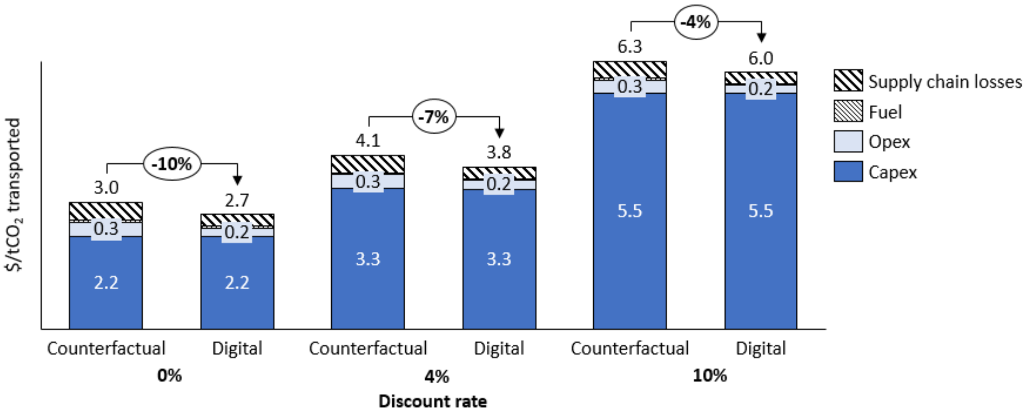

Figure 6-8 Effect of applied discount rate on projected reductions in levelised lifetime cost for an offshore pipeline operating in 2040

6.8 Risks and challenges to CCS deployment

Key challenges facing CCS deployment are summarised in Table 6-5.[160,161,162, 163, 164, 165]

Table 6-5 Summary of key risks and challenges to CCS deployment

Category	Risk or challenge
Economic and financial	**Storage liability** post-closure, uncertainty and scale of potential cost due to uncertainty in future carbon process and in the scale of potential leakage, difficult to insure against
	Cross-chain risk of chain needing to be developed without guarantee that all elements will be able to work properly
	Natural monopolies of transport and storage networks
	Low carbon cost resulting in low incentive to invest in CCS (lack of market)
Political	**Dependence of revenue and profitability** on government policies
	Public acceptance dependent on risk perception of the sustainability of CCS and the possibility of leakages
Technical viability	**Capture site challenges** footprint of capture plant, need for ducting, particularly where multiple vents are present
	Industrial plant integration risks low opportunity for retrofit, downtime required for retrofit, increased operational complexity, impact on product quality, low familiarity of industrial sectors with gas separation
	Power plant integration risks Low operability of capture technology due to part-load limitations of compressor and slow startup/shutdown
	Coordination of projects: dependencies of capture and storage on each other resulting in delays; coordination of timescales of each chain component
	Accessibility of global storage capacity (accessible pore volume) that is otherwise expected to be limited by reservoir pressurisation, particularly in lower quality reservoirs required beyond the first generation of storage projects
	Proving storage capacity of a given site to a sufficient level to enable a financial investment decision (FID) to be taken
	Competition between CCS and oil and gas sector for staff experienced staff and drilling equipment necessary for exploration, which could represent a bottleneck in the long term
All	**Potential for CO_2 release** both through leakage from permanent storage sites and through accidental release (such as in the event of a pipeline disaster), representing an environmental risk, public perception risk and a financial risk through the uncapped liability of future storage leaks

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[160] *CCS market mechanisms* (2018) Element Energy & Vivid Economics
[161] *Policy priorities to incentivise large scale deployment of CCS* (2019) Global CCS Institute
[162] Five keys to unlock CCS investment (2017) International Energy Agency
[163] S. Budinis, et al. (2018) *Energy Strategy Reviews*, (22), p 61-81
[164] *An Executable Plan for enabling CCS in Europe* (2015) Zero Emissions Platform
[165] *Business models for CCUS* (2019) Element Energy for UK Government (BEIS)

6.9 Current developments in CCS

A range of technological solutions aiming to address challenges in CCS deployment are under development. Examples include:

- **Modular systems** – which aim to reduce costs and address issues of plant integration by providing standardised capture technology modules. Capex reductions of over 40% are estimated compared to conventional design, due to reductions across engineering, fabrication, installation and start-up costs.[166] Currently available with capture capacities of 10,000-100,000 tCO_2 per year, these units are due to be trialled in a waste-to-energy plant in the Netherlands from 2021.[167]
- **Novel capture technologies** – such as metal organic frameworks (MOFs),[168] which aim to improve CO_2 adsorption and therefore capital costs and energy requirements of capture
- **Utilisation** – conversion of CO_2 to useful products (such as CO_2-to-aggregate,[169] CO_2-to-polymers[170] and CO_2-to-fuels[171]) provides an alternative pathway for removing captured CO_2 to avoid risks associated with storage site development and to provide revenue streams for the captured carbon; however, these solutions have been developed to varying degrees of maturity and significant storage solutions will still be required to abate CO_2 on a large-scale.
- **Direct air capture** – aims to directly remove CO_2 from the air, avoiding the need for post-combustion capture on site; however, these technologies currently have high costs and are subject to the same economic challenges.[172]

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[166] https://akersolutions.com/news/news-archive/2019/aker-solutions-signs-carbon-capture-contract-with-twence-in-the-netherlands/

[167] https://www.thechemicalengineer.com/news/aker-solutions-to-provide-carbon-capture-technology-to-waste-to-energy-plant/

[168] K. Sumida *et al.* (2012) Chemical Reviews vol 112, p. 724-781 doi: 10.1021/cr2003272

[169] https://oco.co.uk/

[170] http://www.ccccx.net/en/technology.asp

[171] https://co2cert.com/

[172] *Greenhouse Gas Removal* (2018) Royal Society and Royal Academy of Engineering

IEA Greenhouse Gas R&D Programme

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