National Physical Laboratory

Energy transition:

Measurement needs for carbon capture, usage and storage

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Contents

National Physical Laboratory
The National Physical Laboratory (NPL) is the UK's National Measurement Institute. At the heart of our mission is delivering impact by disseminating research and measurement best practice and traceability for the economic and social benefit of the nation.

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Glossary

BECCS	Bioenergy with carbon capture and storage
BEIS	Department for Business, Energy and Industrial Strategy
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CCUS	Carbon capture, usage (or utilisation) and storage
CCU	Carbon capture and usage (or utilisation)
COP26	UNFCCC's 26th Conference of the Parties
CO_2	Carbon dioxide
DAC	Direct air capture
DACCS	Direct air capture with carbon storage
Defra	Department for Environment, Food and Rural Affairs
EA	Environment Agency
EC	European Commission
ECV	Essential climate variable
EMN	European Metrology Network
EMPIR	European Metrology Programme for Innovation and Research
EO	Earth Observation
EOR	Enhanced oil recovery
ETS	Emissions Trading System
EU	European Union
GGR	Greenhouse gas removal
GHG	Greenhouse gas
$GtCO_2$	Gigatons of carbon dioxide
HENG	Hydrogen enriched natural gas
HMG	Her Majesty's Government (UK Government)
HSE	Health and Safety Executive
IMO	International Maritime Organisation
ISO	International Organisation for Standardisation
LCA	Life cycle assessment
LNG	Liquified natural gas
Mt	Million tonnes
NEL	TÜV SÜD National Engineering Laboratory
NMI	National Metrology Institute
NPL	National Physical Laboratory
NZT	Net Zero Teesside
ppm	Parts per million
SI	International System of Units
SME	Small to Medium sized Enterprise
SMR	Steam methane reformation
SNG	Synthetic natural gas
TC	Technical committee
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organisation
ZCH	Zero Carbon Humber

Executive summary

There are a number of technologies that could assist the UK in reaching its legislative target of net zero greenhouse gas emissions by 2050 [1]; but only one that, regardless of other policy decisions, has been identified as essential: carbon capture and storage (CCS). The Committee on Climate Change (CCC) have noted that greenhouse gas removal (GGR) technologies such as CCS will play an important role in offsetting 'difficult-to-cut emissions' [2], for example from heavy industry. This is a position supported by the UK Government (HMG), who have stated that CCS is 'necessary to meet national and international climate change targets' [3] and have highlighted the UK's potential for becoming a 'world-leader in technology to capture and store harmful emissions' as part of the '*Ten Point Plan'* for a Green Industrial Revolution, announced in November 2020 [4]. The protection and expansion of natural carbon sinks such as forests and oceans will also be key to tackling anthropogenic emissions alongside the utilisation of industrial CCS as a transitionary decarbonisation tool. The recycling of captured carbon dioxide (CO_2) for use in other products such as carbonated drinks, cement and fertiliser production would provide further economic and climate benefits, which is why 'usage' has also been included in the scope of this report.

HMG have noted that this decade will be 'critical' for carbon capture, usage and storage (CCUS), and with an aim of deploying CCUS at two industrial clusters by the mid-2020's it is important to identify and address any measurement needs or challenges that may arise [5]. As the UK's National Metrology Institute (NMI), the National Physical Laboratory (NPL) is tasked with providing measurement expertise, services and the underpinning metrological infrastructure for standards traceable to the International System of Units (SI), in support of government policy and industry needs.

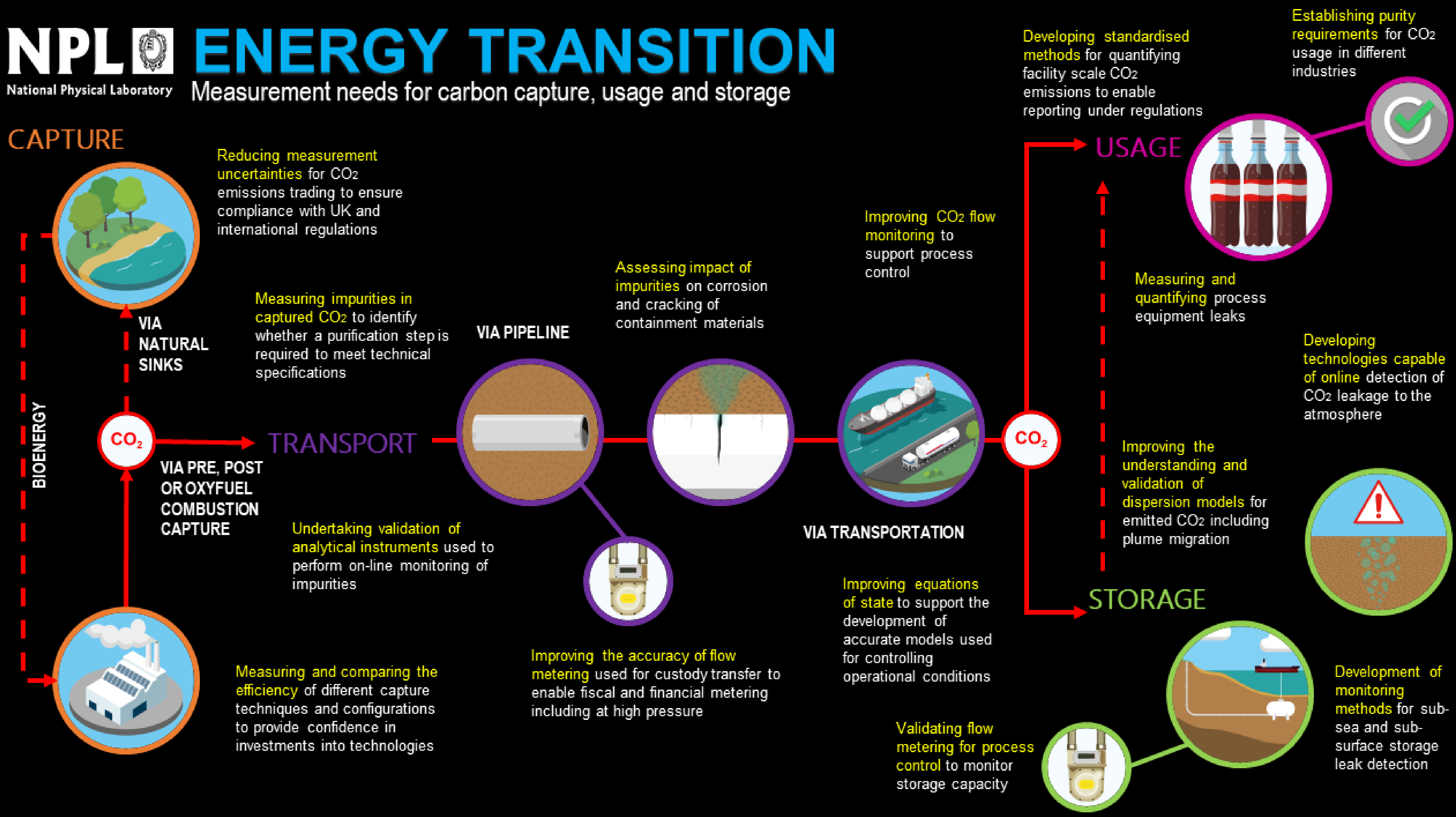
There are specific measurement capabilities that need to be developed to support the effective and safe deployment of CCUS in the UK. NPL, together with TÜV SÜD National Engineering Laboratory (NEL) – who deliver the UK's National Measurement System (NMS) alongside several other institutions[1] – have identified priority measurement needs and potential challenges through stakeholder engagement and a webinar series held in October 2020. NPL have further conducted a literature review of reports and strategies for CCUS in the UK to provide context for the role that measurement can play, alongside a summary of measurement needs and challenges for carbon capture (Chapter 2), transport (Chapter 3), usage (Chapter 4) and storage (Chapter 5).

The highest priority measurement needs identified through stakeholder input and expert judgement include:

- Measuring and comparing the efficiency of different capture techniques and configurations to provide confidence in investments into technologies;
- Improving equations of state to support the development of accurate models used for controlling operational conditions;
- Improving CO_2 flow monitoring to support process control, and;
- Improving the understanding and validation of dispersion models for emitted CO_2 including plume migration, to support safety assessments.

The UK has an internationally prominent measurement capability, as well as established research institutions who can work together to ensure these measurement needs and challenges are met. The infographic on the following page visually summarises these needs.

[1] NPL, NEL, LGC, Regulatory Delivery (part of BEIS), National Gear Metrology Laboratory (NGML), National Institute for Biological Standards and Control (NIBSC)



NPL
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ENERGY TRANSITION
Measurement needs for carbon capture, usage and storage
CAPTURE
Reducing measurement uncertainties for CO2 emissions trading to ensure compliance with UK and international regulations
VIA NATURAL SINKS
BIOENERGY
CO2
VIA PRE, POST OR OXYFUEL COMBUSTION CAPTURE
Measuring impurities in captured CO2 to identify whether a purification step is required to meet technical specifications
Undertaking validation of analytical instruments used to perform on-line monitoring of impurities
Measuring and comparing the efficiency of different capture techniques and configurations to provide confidence in investments into technologies
TRANSPORT
VIA PIPELINE
Assessing impact of impurities on corrosion and cracking of containment materials
Improving the accuracy of flow metering used for custody transfer to enable fiscal and financial metering including at high pressure
Improving CO2 flow monitoring to support process control
VIA TRANSPORTATION
Improving equations of state to support the development of accurate models used for controlling operational conditions
CO2
USAGE
Developing standardised methods for quantifying facility scale CO2 emissions to enable reporting under regulations
Establishing purity requirements for CO2 usage in different industries
Measuring and quantifying process equipment leaks
Developing technologies capable of online detection of CO2 leakage to the atmosphere
Improving the understanding and validation of dispersion models for emitted CO2 including plume migration
STORAGE
Validating flow metering for process control to monitor storage capacity
Development of monitoring methods for sub-sea and sub-surface storage leak detection

1 Introduction

In 2019, the UK became the first major economy to pass legislation that committed to a target of net zero greenhouse gas (GHG) emissions by the year 2050, and by 2045 in Scotland [1]. The net zero target was introduced with the aim of mitigating the impacts of climate change whilst reducing pollution of the natural environment. Much of the current and predicted climate change that is experienced globally is caused by GHG's such as carbon dioxide (CO_2) becoming trapped in the Earth's atmosphere, causing a heating effect. As of September 2020, the global average CO_2 content in the atmosphere was around 411 parts per million (ppm) [6], which is 'higher than at any point in at least the past 800,000 years' [7]. However, there are uncertainties in the scale, timeline and geographical nature of the impacts of climate change on society and hence in the relative value of differing mitigation strategies. These uncertainties mean that the consequences for society, in both action and inaction, are dramatic and far-reaching. CCUS provides an effective transitionary tool to deal with these uncertainties and to enable progress towards net zero whilst allowing the economy to time to adapt.

There are several sectors within the UK economy that produce significant carbon emissions that will be a challenge to abate. Business and industry are substantial contributors, accounting for ~25% of the country's total emissions [8]. Power stations account for ~18% of the total UK CO_2 emissions, however this amount has decreased slowly since 1990 with the proliferation of renewable energy sources alongside efficiency and technological improvements [8]. These sectors are vital to the UK economy, and as such, achieving net zero whilst retaining competitiveness will be essential. Transitioning away from the combustion of fossil fuels to cleaner energy sources and reducing process emissions will be central to the effort to tackle climate change and to abating CO_2 emissions from these sectors. However, there remains a need to remove CO_2 from processes where decarbonisation is currently unachievable, as well as reduce the levels already in the atmosphere for example through direct air capture (DAC) as a last resort.

The CCC stated in their 2019 'Net Zero' report that greenhouse gas removal (GGR) technologies such as carbon capture and storage (CCS) will play an important role in offsetting 'difficult-to-cut emissions' [2] and according to the House of Commons Committee of Public Accounts, "without CCS, there is a gap in the government's plans for achieving decarbonisation at least cost while ensuring a secure supply of electricity" [9]. The Department for Business, Energy and Industrial Strategy (BEIS) also stated in their 2020 response on business models, that carbon capture, usage and storage (CCUS) alongside low carbon hydrogen 'will play a vital role in levelling up the economy, enabling the low carbon economic transformation of our industrial regions, and supporting high value jobs' [5]. Hydrogen and CCUS both feature as part of HMG's *'Ten Point Plan'*, announced in November 2020, which aims to 'create and support up to 250,000 highly-skilled green jobs in the UK' [4].

CCUS and GGR are processes that involve the capture, storage or utilisation of CO_2 that would otherwise have entered the atmosphere. Natural processes exist that already perform this function, known as 'carbon sinks', within ecosystems such as the oceans and forests. The process of photosynthesis allows for CO_2 to be sequestered and stored within 'living biomass, soil and litter' in forests [10] and similarly in marine plants which sequester around 48% of the total CO_2 produced through burning fossil fuels, making the oceans an essential part of the Earth's carbon cycle [11]. Nonetheless, these natural sinks cannot be solely relied upon to solve the climate issue and their efficacy is in fact being damaged through positive feedback loops created by climate change, such as impacted ocean circulation and increased forest fires due to hotter conditions.

In this report, the National Physical Laboratory (NPL) will primarily focus on measurement needs and challenges relating to CCUS for industrial decarbonisation of large-scale emitters of CO_2 such as heavy industry or power plants, however we will briefly explore bioenergy with carbon capture and storage (BECCS), direct air capture with carbon storage (DACCS) and the role of natural processes such as afforestation, environmental protection and restoration.

1.1 CCUS in the UK

Historically, CCUS has experienced cycles of interest in the UK, starting in 2003 when the UK Government's (HMG) '*Energy White Paper*' stated that CCS 'may offer a promising way forward' [12]. Over the years, progress was stalled by a number of factors including 'high infrastructure costs, lack of commercial viability, and concerns around safety', however, since 2017, activities have begun to be re-established and some promising progress has been made [13]. Figure 1 outlines CCUS activity undertaken by HMG from 2017 to the present day (as of November 2020).

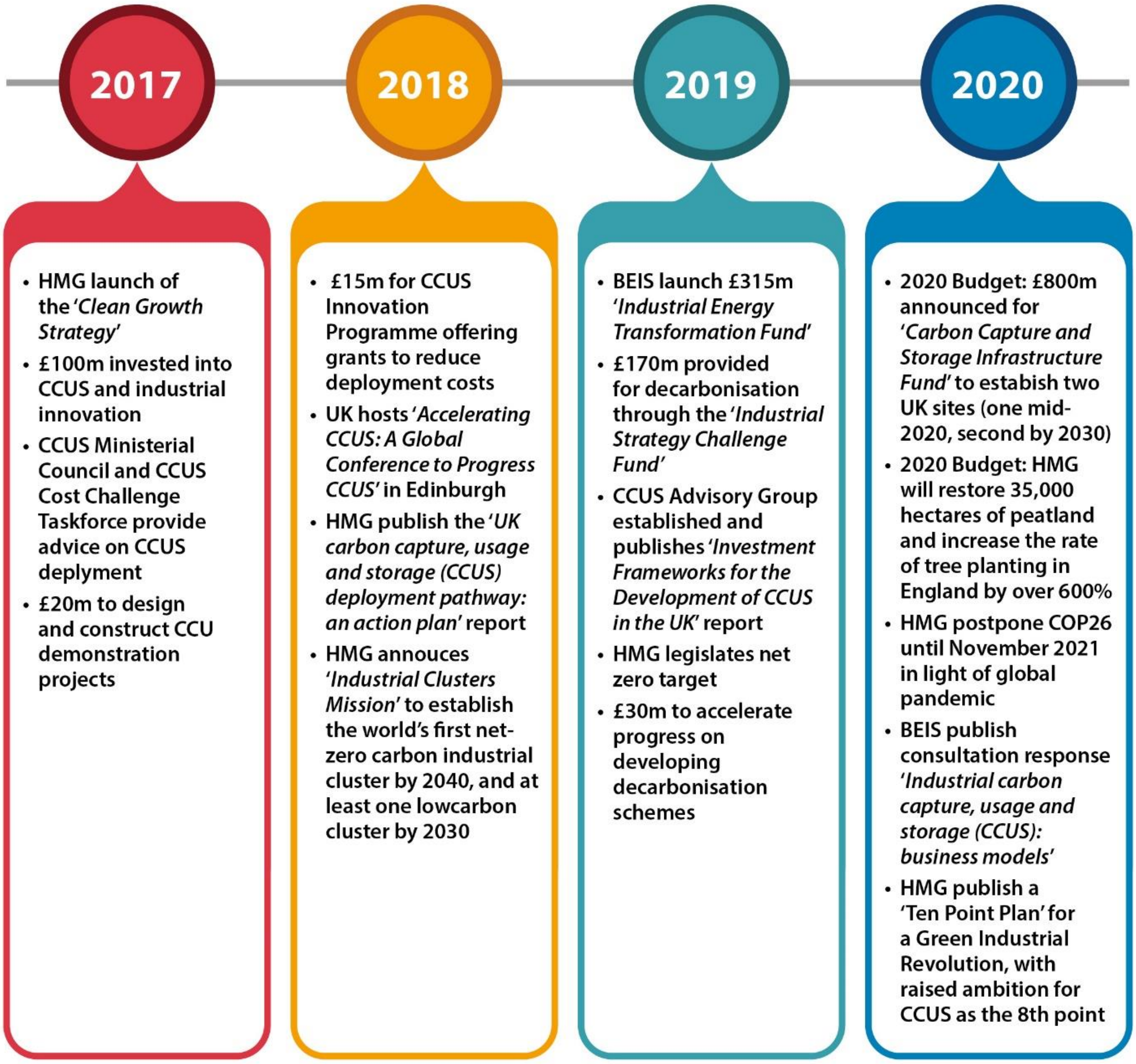

Figure 1: Timeline of HMG's CCUS activity between 2017-20

HMG, in collaboration with Italy, were set to host the United Nations Framework Convention on Climate Change's (UNFCCC) 26th Conference of the Parties (COP26) in November 2020, however due to a global pandemic, the conference was postponed until November 2021, which alongside uncertainties relating to the UK's exit from the European Union (EU) saw progress towards net zero hindered. Nevertheless, in the 2020 budget, HMG announced £800 million for a *'Carbon Capture and Storage Infrastructure Fund'* alongside restoration of '35,000 hectares of peatland' and an increased tree planting rate of 'over 600%' across England [14].

This showed efforts in addressing emissions through both industrial decarbonisation funding and restoration of natural carbon sinks. Furthermore, in November of 2020, HMG announced a '*Ten Point Plan'* for how the UK will remove its contribution to climate change by 2050 through a Green Industrial Revolution. This included a specific point on CCUS with the ambition of making the UK 'a world-leader in technology to capture and store harmful emissions away from the atmosphere, with a target to remove 10 Mt of carbon dioxide by 2030, equivalent to all emissions of the industrial Humber today' [4].

Although emissions produced directly by the UK have declined due to environmental policies, imported emissions as a result of international trade flows remain a significant contributor to the UK's total GHG inventory [15] and it is clear that if the UK is to meet its net zero target by 2050, and the world is to meet the Paris Agreement target of limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C [16], then international collaboration will be essential. HMG have supported international activity relating to CCUS through its International Climate Fund[2] [17], co-founding of the Translational Energy Research Centre with the European Commission (EC) as part of the '*CCUS Innovation Programme'*[3] and participation in the Carbon Sequestration Leadership Forum[4] and Mission Innovation[5] as examples.

The UK's unique geography creates opportunities and challenges pertaining to CCUS deployment. It is estimated that for the UK to reach net zero emissions by 2050, between 75-175 Mt of CO_2 equivalent will need to be removed by CCUS annually [2], and the UK boasts over 500 identified offshore storage sites that could meet this need [18]. The UK's largest industrial clusters requiring decarbonisation are dispersed predominantly around the coastline, many with access to these storage assets; the most significant in terms of emissions being Humberside in north-east England which produces 12.4 $MtCO_2$ per year [19]. CCUS is a tangible decarbonisation solution within the majority of these industrial clusters, alongside other potential mitigation solutions such as fuel switching (for example to hydrogen), energy efficiency improvements and industrial symbiosis through shared resources and waste products.

There are a small number of demonstration and pilot projects underway in the UK including '*Acorn CCS*' in St Fergus, Scotland[6], a BECCS in trial at Drax Power Station in North Yorkshire[7] and the carbon capture and hydrogen supply project '*HyNet*' which is looking to store CO_2 in the East Irish Sea[8]. HMG's target is to have the first CCUS site in operation by mid-2020 and NPL will work with government, academia and industry, both domestically and internationally, in support of these projects and reaching the net zero target.

[2] https://icai.independent.gov.uk/wp-content/uploads/ICAI-Report-International-Climate-Fund.pdf (page 45)
[3] https://terc.ac.uk/translational-energy-research-centre-2/
[4] https://www.cslforum.org/cslf/
[5] http://mission-innovation.net/our-work/innovation-challenges/carbon-capture/
[6] https://www.actacorn.eu/
[7] https://www.drax.com/about-us/our-projects/bioenergy-carbon-capture-use-and-storage-beccs/
[8] https://hynet.co.uk/phase-1/

1.2 Purpose of this report

As the UK's National Metrology Institute (NMI), NPL has a responsibility to address priority measurement needs and challenges affecting economic prosperity and quality of life of UK citizens. Addressing these needs and challenges will require both the right expertise and a harmonised effort from funding bodies, industry, research institutes, standardisation bodies and policy makers. The UK has an internationally prominent measurement capability, as well as established research institutions, which could enable us to be at the forefront of CCUS research, development and deployment. BEIS provide funding to NPL and other designated institutes within the UK through the National Measurement System (NMS) because of the substantial impact measurement science has on UK society and the country's economic success [20]. The purpose of this report is to analyse the processes behind the capture, transportation, usage and storage of CO_2, and identify and prioritise the measurement needs and challenges that may have the potential to create hurdles and bottlenecks in progress towards the deployment of CCUS in the UK. NPL uses these prioritised measurement needs to formulate programmes of work and shape our NMS investment in order to address them.

Processes for the capture of CO_2, including in industrial settings and via natural processes, are discussed in Chapter 2. A robust understanding of how the gas is then transported, including which methods and materials would be needed to reduce any potential environmental impacts are explored in more detail in Chapter 3. The varying techniques for the separation and capture of CO_2 during energy production and industrial processes are likely to impact the quality and therefore potential further usage of the gas itself; the measurement needs and challenges relating to CO_2 usage are further discussed in Chapter 4. This report refers throughout to 'usage' of CO_2, in line with the UK Government's definition of CCUS, but we are aware that the term 'utilisation' is also often applied. For the purpose of this report, these two terms are considered interchangeable. If the captured carbon is to be stored, for example underground in aquifers and depleted gas stores or under the seabed, then a number of measurement needs including leak detection, metering and equations of state will be required, as outlined in Chapter 5.

The conclusions presented in this report, including the high priority measurement needs and challenges outlined in Chapter 6, are based on engagement with stakeholders from across the CCUS supply chain, including information collected during a series of online webinars hosted by NPL and NEL in October 2020, as well as a review of sectoral strategies and reports relating to CCUS conducted by NPL. The report also highlights the areas that will require further investigation and investment, and it could therefore be used to inform calls for collaborative research activities.

2 Capturing carbon dioxide

European Metrology Network for Energy Gases

The European Metrology Network (EMN) for Energy Gases provides measurement science expertise to society and industry to support the implementation of the energy transition to renewable gaseous fuels.

By bridging the gap between research and end-user communities and acting as a central nucleus for measurement science activities, the EMN for Energy Gases will facilitate the deployment of safe, reliable, and diverse energy networks for the future.

NPL on behalf of the EMN for Energy Gases, chaired by VSL, has produced a strategic research agenda (SRA) which discusses current and future trends for energy gases and associated measurement needs. In collaboration with European stakeholders, the EMN has prioritised these measurement needs and challenges that may have the potential to create hurdles and bottlenecks in future energy gas utilisation at the European scale.

The gases considered include:

- Natural gas (including LNG and HENG)
- Hydrogen
- Biogas/biomethane
- CO_2 from CCUS

Examples of priority measurement needs and challenges include flow metering, physical properties, gas composition, gas metrology, materials characterisation, combustion, leak detection and storage.

Further information regarding the EMN for Energy Gases, including the SRA can be found here.

The 'capture' step of CCUS refers to the stage where CO_2 is extracted from its source before it is able to reach the Earth's atmosphere and contribute to the greenhouse effect. There are natural processes that produce CO_2 such as biomass decomposition, volcanoes and wildfires, however this report will focus on anthropogenic sources of emissions only. The Earth also provides naturally occurring carbon capture processes such as through photosynthesis, which allows for significant carbon sinks in environments such as oceans and forests. These natural carbon capture processes will be discussed further in section 2.2.

2.1 Industrial carbon capture

There are several energy production processes such as fuel combustion, oil refining and steam methane reformation (SMR) that produce CO_2 as a by-product which would require capturing to be in line with the net zero target in the UK. At present, some large industrial plants including natural gas processing and ammonia production routinely separate CO_2 to meet process demands, however it is often vented to the atmosphere via the flue gas rather than stored due to a lack of requirement or incentive to do so [21]. Other industrial processes such as cement and chemical production also produce CO_2; these 'foundation industries' (which also include metals such as steel, ceramics, glass and paper production) account for '10% of total CO_2 emitted by UK homes and businesses' [22] and will require deep decarbonisation solutions including CCUS. Methods for the capture and removal of CO_2 from these processes can include:

- **Pre-combustion** capture: where the CO_2 is removed before the conversion of fuel to energy which may involve reforming or gasifying the fuel;
- **Post-combustion** capture: where the fuel is directly combusted using air, which may cause trace elements and contaminants to be present in the CO_2;
- **Oxy-fuel combustion**: which utilises pure oxygen instead of air to perform combustion, and;
- **SMR**: a common process for producing hydrogen from natural gas [23], where natural gas is mixed with steam, heated to over 815 °C and reacted in the presence of a nickel catalyst to produce hydrogen (H_2) and carbon monoxide (CO), which is then converted to CO_2 via a water gas shift reaction [24].

Hydrogen production and CCUS

Hydrogen has the potential to decarbonise electricity generation, transport and heat. Similarly to CCUS, it has historically experienced cycles of interest within the UK and internationally but has often been discounted due to the lack of maturity and cost of the technologies required (for example fuel cells and electrolysers), and a lack of evidence of not only their performance but their ability to be commercialised. However, in recent years, discussions around hydrogen in the UK have begun to shift from hypothetical debates to practical rollouts. Hydrogen features as the 2nd point in HMG's *'Ten Point Plan'*, through which they are 'aiming to generate 5GW of low carbon hydrogen production capacity by 2030 for industry, transport, power and homes, and aiming to develop the first town heated entirely by hydrogen by the end of the decade' [4]. There is an ever-growing evidence base within the hydrogen industry – of roadmaps, reports, projects and practical infrastructure implementations – demonstrating that hydrogen can play a feasible role in the efforts to decarbonise the UK's energy system.

As well as enabling carbon reductions in the electricity and foundation industries, CCUS also allows for the production of 'clean' hydrogen. Almost all of global hydrogen production comes from hydrocarbon sources and SMR currently accounts for around half of this [25]. To meet the UK's decarbonisation targets, it is important that the carbon-based emissions that are produced via SMR are captured and stored (through CCS) to produce 'blue hydrogen'. The deployment of CCS technologies is essential should SMR be pursued as a carbon-neutral method for hydrogen production; hydrogen produced without the use of CCS would create 'grey hydrogen', resulting in large emissions of CO_2 and would therefore not be conducive with the UK's net zero target.

2.2 Carbon capture in nature

Naturally occurring carbon sequestration has allowed for the habitable conditions Earth experiences and currently account for the removal of around half of anthropogenic carbon emissions. Without these natural carbon sinks, a larger proportion of CO_2 entering the atmosphere would remain there, causing ever-warming global temperatures and accelerated climate change that would render the planet inhospitable to humans and most other organisms. The capacity of the natural environment to absorb this proportion of carbon indefinitely is a concern and topic of current research. To avoid significant climate change, a 'balance' must be met in the Earth's carbon cycle, however anthropogenic activity such as the combustion of hydrocarbons for energy, deforestation and land-use change have impacted the efficacy of these natural sinks.

Long term observations of Earth system variables, from Earth Observation (EO) satellites and in situ observation networks, are vital for providing the monitoring of the environment necessary to understand the inter-play of natural and anthropogenic processes, the response of the Earth system to these inputs, as well as to determine the efficacy of our policies to limit environmental and climate change. Historically, in-situ observation networks were the mainstay of the monitoring effort, but the increased sophistication of the in-orbit EO network now supplements this, adding truly global coverage. The importance of the in-orbit contribution to environmental monitoring will only grow into the future. Key environmental parameters have been captured in the World Meteorological Organisation (WMO) defined Essential Climate Variables (ECVs), with those directly related to carbon cycle sinks including soil moisture, permafrost cover, soil carbon, above-ground biomass and inorganic carbon in oceans; each an indicator of how carbon sinks are impacted by anthropogenic activity over time [26].

Globally-collected environmental parameters are used to inform models that are in turn used to inform government policy and by industry, citizens and NGOs. Policy drives behavioural change, that lead to changes in emissions (both reductions and increases) and land use change, for example afforestation rates, which would increase natural sequestration of carbon by trees. EO datasets can then not only track climate change but can also be used to determine the efficacy of the implemented policy, allowing adjustments in policy to be made to maximise the positive impact on the natural world. Observations, from space and on-ground, are a critical link in our managing of our environment, and the accuracy, veracity and usability of this data is crucial to ensuring global efforts are science-driven, targeted and that pledges are honoured.

Experts in several organisational groups at NPL are actively working within the fields of metrology for climate and emissions, including measurements related to changes in natural carbon sinks. Some of the measurement capability that NPL holds for observing and monitoring these changes include:

- **Applying metrological principles** to ascertain the quality of climate data or information and the assessment and reporting of its provenance within metadata;
- **Quantifying the quality** of a climate measurement result, with respect to an agreed international reference;
- **Undertaking measurements within 'real-world' or laboratory conditions** and establishing 'best practices' for representative sampling, traceability and uncertainty;
- **Ensuring the accuracy, traceability and consistency** of climate and emissions measurements undertaken by different instruments or organisations for the same purpose;
- **Carrying out research, development and validation** of new tools for undertaking measurements in all environments including space, and;
- **Maintaining primary reference facilities** which provide a source of traceability for climate and emissions measurements and measured quantities in the SI in the UK and more widely.

Earth and climate observation

Space-based in-orbit sensors offer a unique opportunity to capture truly global environmental data over climate-relevant timescales. EO data allows us to monitor the state of natural carbon sinks such as forests and oceans through parameters such as forest coverage and ocean colour.

NPL are supporting the international and national space agencies (ESA, EUMETSAT, UKSA, CNES) with a wide range of capability relating to Earth and climate observation that can support the understanding of and improvement of the measurement and monitoring of global carbon stocks, for example, through:

1. Building facilities and performing pre-flight calibration of satellite sensors (both direct atmospheric GHG sensors and surface sources and sinks) to ensure the collected data is accurate and well understood;
2. Applying metrological principles to the generation of derived products relevant to carbon cycle parameters and creating robust uncertainties in the scientifically important quantities, and;
3. Further applying those quality metrics and principles between sensors and networks, allowing interoperable use of multiple sensors ensuring the trustability of global land and ocean carbon stock datasets.

To find out more about NPL's capability in this area, please visit our website.

There is also a drive towards better understanding the role that anthropogenically managed natural sequestration could play through the use of bioenergy with CCS, or ‘BECCS’. It has been identified as a keystone technology in many integrated assessment models that look to advise on how the Paris Agreement[9] may be met [27]. The BECCS process involves using biomass feedstocks such as energy crops, residual agricultural products and trees to not only capture CO_2 from the atmosphere throughout the growing process, but to deliver energy via combustion or conversion to biofuels [28]. When CCS is added to this process, it means that more CO_2 is being removed from the atmosphere than is emitted, making BECCS a ‘carbon negative’ solution [29]. The only post-combustion BECCS project globally is at the Drax Power Station[10] in the UK, who are currently starting work on converting biomass units to BECCS units that could capture 4 million tonnes per year of CO_2 [30]. However, there are some challenges that will require addressing for BECCS to play a role in the UK’s decarbonisation efforts, including public acceptance, the sustainability of the biomass used through life cycle assessments, the scalability of BECCS and how it would fit within the UK’s accounting and emission reporting systems [27]. Several of these challenges could be supported through the use of robust measurement science.

Direct air capture

Direct air capture (DAC) and storage of CO_2 – often termed DACCS – is a process whereby technologies are utilised to remove CO_2 that is already in the atmosphere. According to the IPCC, ‘negative emissions technologies’ will be required to meet the Paris Agreement and DACCS could support this effort whilst natural solutions such as trees and peatlands are expanded and restored [31]. DACCS is therefore seen as a complementary negative emission solution that could significantly reduce mitigation costs [32].

There are currently 15 DAC plants in operation internationally, with the majority selling on the captured CO_2 for further usage; the first large scale DAC plant is being developed by *Carbon Engineering* in the USA, which will ‘capture up to 1 $MtCO_2$ each year for use in enhanced oil recovery and could become operational as early as 2023’ [33]. HMG are exploring the potential of DACCS and are planning to launch an innovation programme ‘to develop and demonstrate direct air capture of CO_2 and other greenhouse gas removal technologies (GGR) in the UK’ [34].

At present, there are main two approaches to DAC: passing air through chemical solutions or through solid sorbent filters which chemically bind with the CO_2 [33]. Other approaches are also being investigated, such as catalytic conversion. Ensuring the efficiency and capture rates of these processes will be important should they be deployed as solutions for reaching net zero. Furthermore, understanding whether impurities are introduced through the DACCS process will be essential, as dependent on the method of transporting the CO_2, some impurities can impact pipeline integrity (explored in Chapter 3) and if it is to be used as a feedstock for another process, the quality of the CO_2 needs to be assured (explored further in Chapter 4).

[9] The Paris Agreement aims to keep global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C
[10] https://www.drax.com/

2.3 Measurement needs and challenges for carbon capture

The measurement needs and challenges outlined in the summary box below pertain to the deployment of carbon capture for the purpose of industrial decarbonisation predominantly. These include measuring the efficiency of different capture techniques, identifying impurities that may be present in the CO_2 as a result of the capture technique and flow metering of the CO_2. In addition, a focus on CCUS technologies has been made, rather than on natural systems that sequester carbon as outlined in section 2.2.

A summary of the high priority measurement needs for carbon capture, as well as for 'Transport', 'Usage' and 'Storage' (as identified through stakeholder engagement) can be found in Chapter 6. The stakeholders that input into this exercise are listed in 'Annex 2: Contributors'.

Measurement needs and challenges for carbon capture

Measuring and comparing the efficiency of different capture techniques and configurations to provide confidence in investments into technologies in support of CCUS business cases, including full lifecycle analysis and direct measurements

Reducing measurement uncertainties for CO_2 emissions trading to ensure compliance with UK and international regulations

Undertaking real-time measurement of post-capture emissions to enable process control during capture and report emitted substances, for example oxides of nitrogen

Understanding the effect of capture processes on measurement techniques used for reporting regulated pollutants and define reference conditions, for example oxygen and CO_2, to ensure continued compliance

Developing pre-capture flue gas analysis to identify any substances that may impact on solvent performance

Identifying and quantifying new pollutant emissions caused by capture to reduce unintended consequences of CCUS deployment, for example amines and nitrosamines including aerosols

Understanding impurities in captured CO_2 to identify whether a purification step is required to meet technical specifications including cross-reactions between impurities from different processes

Undertaking validation of analytical instruments used to perform on-line monitoring of impurities to indicate degradation of the capture solvent and general indication of capture performance

Supporting standardisation activities for carbon capture

Understanding the potential impact of CCUS capture processes on ambient air, for example atmospheric chemistry of amines and nitrosamines, and determining background levels

Understanding the breakdown products of new solvents as they may impact the purity of captured CO_2 or lead to pollutant emissions

Characterisation and calibration of humidity-measuring instruments for process conditions, to compensate effects of background CO_2 and high pressure

3 Transporting carbon dioxide

Once the CO_2 has been captured, it is transported to either an appropriate storage location or to a facility where it can be utilised in another process. The most common method for the transportation of CO_2 is via pipeline, where it can exist in the gaseous, liquid or supercritical phase, depending on the operating temperature and pressure. CO_2 can also be transported in liquid or solid form via on and offshore vehicles such as trucks, trains and ships [35]. Each of these transportation methods brings with them specific needs and challenges, as discussed further in section 3.2.

In October 2020, the '*Northern Endurance Partnership*' was established between key energy stakeholders[11] involved in the '*Net Zero Teesside*' (NZT) and '*Zero Carbon Humber'* (ZCH) clusters, aiming to 'accelerate the development of an offshore pipeline network to transport captured CO_2 emissions from both NZT and ZCH to offshore geological storage beneath the UK North Sea' [36]. The *'Northern Lights'* project[12], which aims to transport captured and liquified CO_2 from a Norwegian CCS plant via pipeline to offshore North Sea storage some 2,500 m below the seabed, involves the sharing of storage assets between a number of European countries including the UK [37]. These examples of collaboration will be vital for the successful deployment of CCUS. However, around 850 pipelines covering 7,500 km in the UK and Norwegian North Sea shelves are planned to be decommissioned over the next decade, which will incur a significant financial cost [38]. The total amount to be spent on decommissioning on the UK Continental Shelf[13] alone between 2016 and 2025 is an estimated £17.6bn [39]. Some of these costs could be mitigated if these pipelines are repurposed, for example to transport CO_2 for long term storage in depleted oilfields.

There are several measurement-related needs and challenges that the transport of CO_2 may produce, including: assessing the impact of impurities on the integrity of containment materials during CO_2 transport and storage, modelling equations of state and undertaking accurate leak detection along the entire system. It is important that the UK continues to collaborate and share lessons learned in addressing these needs and challenges within international CCUS projects, to mitigate delays to CCUS deployment in line with domestic and global climate targets and commitments.

EMPIR Decarbonising the Gas Grid

A new EMPIR project has been funded that will provide solutions for measurement challenges faced by the gas industry when decarbonising the gas grid (using biomethane, hydrogen enriched natural gas, 100% hydrogen gas grids, and carbon capture and storage).

'Metrology for Decarbonising the Gas Grid' is a joint project through which NPL, as the coordinating body, will be collaborating with other NMI's including BAM, CEM, INRiM, NEL, NPL, PTB, RISE, TUBITAK, VSL and industrial partners including Air Liquide and Enagas.

This project, starting in June 2021, will include:

- Measurement techniques for hydrogen in natural gas;
- Preparation of new Primary Reference Materials and gas standards;
- Testing protocols for analysis of impurities in biomethane;
- Development of new flow metering capability;
- Validation of devices for measuring physical properties, and;
- Development of new traceable methods for monitoring and quantifying carbon dioxide leaks from storage sites.

[11] Partnership between BP, Eni, Equinor, National Grid, Shell and Total
[12] https://northernlightsccs.com/en/about
[13] The UK continental shelf includes parts of the North Sea, the North Atlantic, the Irish Sea and the English Channel

3.1 Regulations and standards

There are regulatory frameworks in the UK and internationally that govern the transportation of gases via pipelines and shipping [40]. Although CO_2 has been transported by ship between European countries as a commodity for several years, it faces different international regulatory frameworks if it is being transported for the purpose of offshore storage, which include 'environmental legislation, monitoring and reporting guidelines, safety procedures and CO_2 storage regulations' [41]. In the UK, the Environment Agency (EA) is tasked with ensuring compliance with the current (as of 2020) EU Emissions Trading System (EU ETS), which is an international GHG emissions trading system that applies to power stations, oil refineries, offshore platforms and foundation industries such as steel, cement and chemicals [42]. The EA also permit the geological storage of CO_2 through '*Environmental Permitting Regulations*'[14], with the Oil and Gas Authority (OGA) being the licensing authority. As of 2019, an amendment to the *'London Protocol'*[15] meant that CO_2 was able to be transported across international boundaries for offshore storage, which removed a significant legal barrier that faced the deployment of CCUS [43]. Other regulatory frameworks applicable to CO_2 transport include:

- the EU ETS Directive (until 30 April 2021);
- the EU CCS Directive;
- the UN Convention on the Law of the Seas;
- the International Convention for the Safety of Life at Sea, and;
- the IMO International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk.

Measurement has a vital role to play in ensuring regulations and standards are met. If, for example, the CO_2 is transmitted along pipelines, 'local, regional or transboundary assessment of potential significant environmental impacts on the natural areas' would be required in case leakage occurs [44]. Removing the risk of leaks from the CCUS process will be critical to ensure its viability as a carbon neutral solution. Furthermore, 'the presence of large amounts of impurities during the compression stage could lead to large inefficiencies or cause corrosion of storage/pipeline materials', which could also cause the CO_2 to leak [23]. This risk can be minimised by ensuring that harmful impurities are not present in the CO_2 before the storage step, for example through the use of amine scrubbing post-combustion, which would produce a stream of pure CO_2 that can be liquefied before transporting for storage or usage. Amine scrubbing captures 85 – 90% of the CO_2 from flue gas dependent on the type of scrubbers used, and the purity of the CO_2 following this process can be better than 99.95% [45].

Before being transported through pipelines, the CO_2 is usually dehydrated to ensure levels of water are below 50 μmol mol^{-1} [23]; this is because the presence of high amounts of water may lead to condensation issues, and additional impurities, such as hydrogen sulphide (as a result of the origin of the natural gas that has passed through the NTS), could dissolve in the water to generate a corrosive environment [46]. Due to this and several other risks and uncertainties relating to CO_2 pipeline transportation (for example corrosion, fracture propagation, impacted saturation pressure and flow intermittency), the UK's Health and Safety Executive (HSE) have stated that 'any proposal to change the fluid conveyed will require a re-assessment of the original pipeline design to ensure that the pipeline is capable of conveying

[14] https://www.legislation.gov.uk/uksi/2019/39/made
[15] 1996 Protocol To The Convention On The Prevention Of Marine Pollution By Dumping Of Wastes And Other Matter, 1972 (as amended in 2006) https://www.epa.gov/sites/production/files/2015-10/documents/lpamended2006.pdf

the fluid safely' under UK and European standards[16] and the *'Pipelines Safety Regulations 1996'* [47, 48]. As CCUS continues to be developed in the UK and internationally, it will be important to ensure that regulations and standards are robust and fit for purpose, without creating bottlenecks. This not only relates to the safety and efficacy of transport and storage mechanisms, but also to the CO_2 gas itself, particularly if is it to be reused as a feedstock in another process. Standards relating to CO_2 quality for a variety of uses are discussed in section 4.1.

Integrity of CCUS pipelines

Corrosion and environment assisted cracking of pipeline materials is a critical safety issue associated with transport of CO_2 from power stations to large scale storage facilities such as depleted oilfields. The presence of CO_2 on its own is not an issue – the problem is associated with impurities, particularly water, that are introduced into the product at various stages in the process.

More accurate determination of dewpoint and the establishment of more reliable thresholds for impurity levels in the CO_2 stream would help to de-risk the business case for investment and provide greater confidence in the safe use of pipelines for transport of dense phase CO_2. NPL is adapting its existing oil and gas corrosion research capabilities to address these issues in collaboration with industry, academia and standards bodies.

The introduction of standards in this area will be a key step in supporting industry to scale up from existing CCUS demonstration projects to large scale deployment of the technology.

To find out more about NPL's work on corrosion, visit our website.

3.2 Measurement needs and challenges for carbon transport

As previously mentioned, there are a number of potential measurement needs and challenges relating to the transportation of CO_2. Based on input from internal experts, industry stakeholders and a literature review, NPL have identified these needs and challenges relating to carbon transport in the box below. Those deemed 'highest' priority by contributors to this report (listed in Annex 2: Contributors) and therefore requiring the most immediate attention from the measurement community have been summarised in Chapter 6 of this report.

[16] (1) DNV RP-J202 – Design and Operation of CO_2 Pipelines (2010); (2) Energy Institute – 1301 CO_2 Good Plant Design; (3) Energy Institute – 1302 CO_2 Hazard Analysis.

Measurement needs and challenges for carbon transport

Assessing of integrity of containment materials in the presence of high pressure CO_2 to avoid corrosion and cracking of pipelines

Assessing the impact of impurities on the corrosivity of CO_2 at high pressure

Developing standard test methods for corrosion and cracking of pipelines and pressure vessels

Improving equations of state to support the development of accurate models used for controlling operational conditions

Developing gas metrology infrastructure to support purity measurements

Improving the accuracy of flow metering used for custody transfer to enable fiscal and financial metering including at high pressure

Developing and validating techniques for pipeline leak detection to be able to efficiently monitor and locate leaks along pipelines

Producing methods for component level CO_2 leak detection and quantification using technologies such as sniffing and optical gas imaging

Developing a purity specification including amount fraction thresholds for key impurities

Assessment of the potential for reusing existing pipelines to reduce decommissioning costs and stranded assets as a result of the energy transition

Gas metrology research at NPL

Gas quality measurements are required in CCUS processes to:

- Monitor for impurities that could be toxic, damage equipment and pipelines or lead to operational inefficiencies;
- Ensure accurate flow metering, and;
- Calculate physical property measurements to understand operational conditions.

NPL have started to develop the required gas analysis methods and Primary Reference Materials to support these measurements. A technical specification was developed (NPL Report ENV23) which provides the key impurities and relevant amount fraction thresholds that NPL are using as guidance to develop a traceable metrology infrastructure.

One of the key issues with preparing Reference Materials is stability; reactive species can adsorb to cylinder walls. CO_2 also liquefies in a gas cylinder at around 40-50 bar which can lead to changes in gas composition. NPL aims to support the UK CCUS industry by providing gas testing, sampling, gas standards and proficiency testing.

To find out more about NPL's gas metrology research, visit our website.

4 Usage of carbon dioxide

'Usage' refers to the repurposing of captured CO_2 (as defined in Chapter 2) as a feedstock for another process, often termed carbon capture and usage or utilisation (CCU). CO_2 usage is a promising solution that would help to abate carbon emissions whilst supporting a circular economy[17] [49]. Utilising waste CO_2 can also help with the business case for CCUS deployment by creating a market for the gas rather than subsidising its long-term storage, however depending on the end use of the CO_2, CCU could be argued as displacement of the emission rather than its ultimate reduction or removal.

According to findings from the '*Global CO_2 Initiative*'[18], the annual market size for CO_2-based products could reach over US$1trillion annually [50], and there are a number of industries and processes that utilise CO_2 that have been outlined in Figure 2. Food and beverage applications can account for 70% of all tonnage consumed in the merchant sector for CO_2 and they bring specific requirements and standards [51]. For CCU to be a viable solution in line with the net zero target, a robust life cycle assessment (LCA) of these processes will be essential to understand the net contribution of specific uses of CO_2 [52]. Undertaking an LCA of CCU is just one example of where measurement can play a key role. The measurement needs and challenges for CO_2 are explored further in section 4.2.

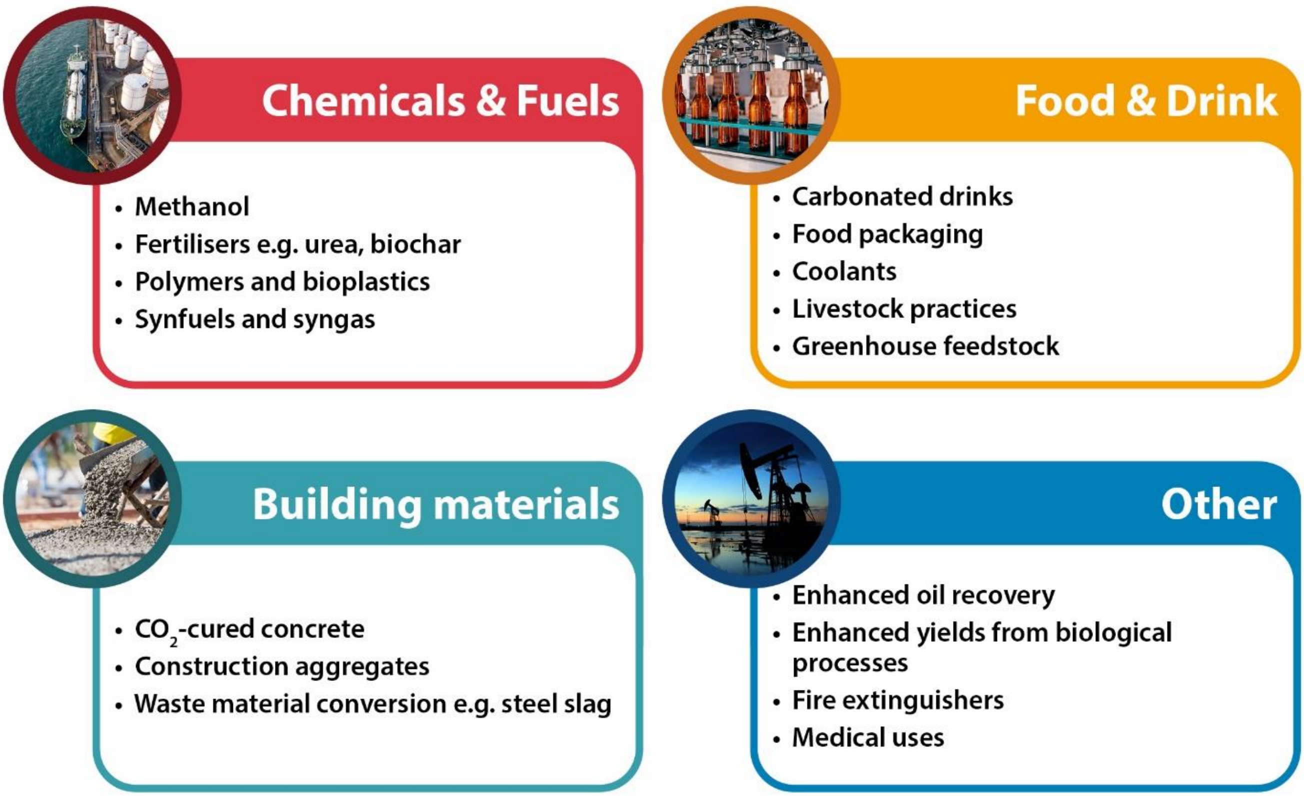

Figure 2: Uses for carbon dioxide across industries

[17] 'A circular economy is based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems'
[18] https://www.globalco2initiative.org/

In the UK, the food and drink industry is by far the largest user of CO_2, accounting for between 50 – 60% of total demand [53]. This is predominantly for the carbonation of water, beer and soft drinks. The food and drink industry is significant to the UK, with an annual turnover of around £90 billion from over 7,000 companies that are mainly SMEs [54]. The summer of 2018 saw a shortage of CO_2 in the UK and across parts of Europe due to supply chain disruption, and this was most acutely felt by the food and drink industry. As such, there is an opportunity for CCU to provide a reliable source of CO_2 to the UK food and drink industry and to mitigate such supply chain shortages. However, an LCA of the CO_2 used in food and drink production will be essential to understand if this type of usage is conducive with climate targets, as to be in line with net zero aspirations, the CO_2 needs to be permanently removed rather than simply displaced. There are some uses – such as for cement and polymer production – that would allow the captured CO_2 to be 'fixed' for a longer time in a new form and are therefore more favourable solutions for meeting net zero in the short term. For example, the UK Centre for Carbon Dioxide Utilisation at the University of Sheffield have developed a technique for producing polyacrylamide from captured CO_2 [55] and are providing further research on LCA's and public perception [56]. However, to truly be delivering on climate targets, CO_2 will either need to be permanently fixed in a new form that will not eventually be broken down or removed from processes such as food and drink or building material production entirely.

CO_2 can also be used in the methanation process to produce synthetic natural gas (SNG), which would displace the need for extracting fossil-derived natural gas [57]. Methanation of CO_2 requires the introduction of hydrogen gas (H_2) to the captured CO_2, which produces methane (CH_4), commonly known as natural gas. The process requires a catalyst (most commonly nickel based), and much of the ongoing R&D relating to methanation is focusing on modification and materials development of these catalysts [58]. The hydrogen used in the methanation process could be produced via electrolysis which would create no net emissions should the electrolyser be renewably powered. However, at the point of use, SNG still creates CO_2 emissions that would require capturing to be in line with net zero and therefore, methanation would be displacing the CO_2 rather than removing it.

HMG has noted the potential of CCU and provided innovation funding of approximately £5.6 million to UK SME's through its '*Energy Innovation Programme'* [59]. In 2019, HMG awarded £4.2 million to Tata Chemicals[19] for the construction of 'the first commercial, purpose-built CCU facility in the UK' which once operational in 2021, will capture 40,000 tonnes of CO_2 per year to produce soda ash and sodium bicarbonate for the 'glass, food, pharmaceutical and chemical manufacturing sectors' [5]. However, HMG is aware there are still uncertainties relating to CCU with regards to LCA's, regulatory frameworks and standards, and NPL are working to support the UK Government and the wider CCUS sector in addressing these uncertainties.

4.1 Regulations and standards

As future markets continue to grow for CCU, each industry and process will bring with them unique requirements in relation to the quality of the CO_2. As such, international engineering and standardisation work will be required to allow both technology and product transfer relating to CCUS. The processes by which the CO_2 was captured, transported and stored can all impact the quality of the gas (as explained in previous chapters), principally through the introduction of impurities that would require removal before the CO_2 can be used. This is particularly the case for the food and drink industry, where the purity of CO_2 is required to be 99% to meet standards set by the Food Standards Agency[20] in the UK. Gases that are to be

[19] https://www.tatachemicalseurope.com/about-us/carbon-capture-utilisation
[20] https://www.food.gov.uk/

used in food or drink need to be produced and supplied in accordance to food grade specifications similar to that provided in the European Industrial Gases Association *'Doc 70/17'* [60]. Other standards pertaining to the quality of CO_2 for food or drink purposes include:

- EC Directive '2000/63/EC laying down specific purity criteria on food additives other than colours and sweeteners'[21];
- EC Council Directive '98/83/EC of 3 November 1998 on the quality of water intended for human consumption'[22];
- Evaluations of the Joint FAO/WHO Expert Committee on Food Additives (JECFA) 'INS No. 290'[23];
- International Society of Beverage Technologists (ISBT) Carbon Dioxide Guidelines[24], and;
- Other local governmental requirements.

4.2 Measurement needs and challenges for carbon usage

CCU remains a growing area of interest in the UK, however further research will be needed that focuses on end-of-life options for reused CO_2 to ensure that the entire process results in negative emissions and is therefore in line with net zero targets. Industry and government are continuing to explore its potential as part of wider CCUS business models and investigating what role it could play in meeting the net zero target. As such, NPL expect further measurement needs and challenges for CCU to come to light as more projects and pilots are rolled out across the UK and wider, however have identified an initial list in the box below with input from industry stakeholders and internal experts.

Measurement needs and challenges for carbon usage

Establishing purity requirements for CO_2 usage in different industries including the supporting gas metrology infrastructure

Developing and validating methods for detecting and quantifying leaks of CO_2 from CO_2 plants, downstream of the supply, including process equipment and piping leaks, to support leak detection and repair

Improving CO_2 flow monitoring to support process control

Developing standardised methods for quantifying facility scale CO_2 emissions to enable reporting under regulations

Performing a life cycle assessment including whether the CO_2 eventually enters the atmosphere or is permanently stored

[21] https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32000L0063
[22] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31998L0083
[23] https://apps.who.int/food-additives-contaminants-jecfa-database/chemical.aspx?chemID=592
[24] https://www.foodsafetymagazine.com/magazine-archive1/december-2000january-2001/international-society-of-beverage-technologists-carbon-dioxide-guidelines/

5 Storage of carbon dioxide

The storage of CO_2 is critical to the role of CCUS as a net zero solution. Ensuring that anthropogenically produced CO_2 is unable to enter the atmosphere should remain the primary driver behind the potential of CCUS technologies. Crucially, the storage mechanism for the CO_2 needs to be reliable and effectively permanent. Seepage or leakage from these storage sites is of primary concern when assessing the viability of CCUS as an effective climate mitigation tool [61]. Should a storage site fail, and the CO_2 be released, all efforts and investments into the initial capture and transportation of the gas would be negated and dependent on its location, could pose a significant risk to human life and natural environment by creating anoxic conditions [62].

Geological formations are currently considered the most promising storage sites for CO_2 [63]. The availability of these geological sites is heavily dependent on a country's geography and access to them can play an important role in the viability of CCUS deployment. Potential storage mechanisms for CO_2 include:

- **Saline aquifers**: these are underground geological formations saturated with brine that are water permeable. Storage of CO_2 via saline aquifers is optimised by injecting the CO_2 as a supercritical fluid. Once injected into the aquifers, the CO_2 is trapped beneath a caprock which is impermeable to gas making them a promising option for long-term CO_2 storage [64].
- **Depleted oil and gas reservoirs**: storing CO_2 in these reservoirs has been proven internationally, whether for pure storage or for EOR purposes [65]. The use of these on and offshore storage sites would reduce decommissioning costs during the transition away from fossil fuels.
- **Mineral carbonation**: injecting CO_2 into reactive rocks can create mineralisation. This would offer a potentially permanent store of CO_2 in geological formations such as basalts and peridotites within onshore and offshore locations [66].
- **Enhanced coal bed methane**: coal that is deemed too difficult or deep to mine can be used to store CO_2, as coal is permeable and would allow the gas to permeate. This process would release the methane that the coal previously absorbed which could be recovered and used [63]. However, during its use, further CCUS measures would require utilising should this process be in line with net zero.

The UK has significant storage capacity; on the UK Continental Shelf there is an estimated 78 $GtCO_2$ capacity with well over 500 potential storage sites based on assessment undertaken by the 'CO_2 Stored'[25] project consortium [67]. This means the UK has a significantly large strategic CO_2 storage resource which could last the country hundreds of years whilst allowing the UK to provide storage capability to other countries [68]. The CO_2 Storage Evaluation Database (created by CO_2 Stored) provides an overview of the UK's CO_2 storage capacity by assessing the potential of saline aquifers and depleted oil and gas fields using parameters such as 'location, storage unit type, lithology, water depths, porosity, permeability, formation thickness, formation depth, formation pressures, and salinity' [69]. The Crown Estate[26] manages most of the UK's territorial seabed where many of these sites are found [70] and can grant permits for storage, along with Scottish ministers for the territorial area surrounding Scotland and the Oil and Gas Authority[27] who also regulate offshore CO_2 storage and maintain the carbon storage public register [71].

[25] http://www.co2stored.co.uk/
[26] https://www.thecrownestate.co.uk/
[27] https://www.ogauthority.co.uk/licensing-consents/carbon-storage/

5.1 Monitoring storage

Essential to the viability of CCUS will be the efficacy of the CO_2 store. This will require a monitoring plan to verify that the injected CO_2 is behaving as expected and that there is no leakage from the site. Furthermore, 'best available techniques'[28] will need to be employed at new and existing sites that will be used to store CO_2. Before the CO_2 is even injected, validated capacity estimates, reservoir simulations and an environmental risk assessment of the site in line with EA regulations will be required, to fully understand any physiochemical processes that may occur during the long term storage of the CO_2 [72].

At present, validation of the quantity of CO_2 captured and sequestered is essential under the EU ETS (which the UK remain under until April 2021), which requires a number of measurement and monitoring needs from the point of capture through to storage. These measurements will not only relate to emissions monitoring and leak detection, but also to the quality of the gas itself. For example, the presence of impurities will have an adverse effect on flow metering, which is necessary for regulatory measurement under the EU ETS [23]. Additionally, the presence of non-condensable impurities can cause issues during the compression stage as they reduce overall density, which would limit storage capacity [64]. However, it is clear that the conditions of storage, such as temperature and pressure, also determine how much effect the presence of non-condensable gases would have to storage capacity [23]. It has been recognised that the levels of hydrogen sulphide and sulphur dioxide in the CO_2 would pose a hazardous scenario for humans and the environment should there be a leak from the storage site, and as such, the gas leak would need to be diluted by up to 500-1000 times to be rendered harmless [23]. Further measurement needs and challenges relating to emissions monitoring and gas quality are detailed in section 5.3.

CO_2 leak detection at NPL

NPL have developed a range of measurement capabilities for detecting, monitoring and quantifying CO_2 emissions from different stages of the CCUS process.

NPL have a long history and expertise in the measurement of point source and fugitive emissions to the atmosphere. NPL have applied this knowledge to the detection and quantification of CO_2. This has included:

- Development and validation of CO_2 optical gas imaging and the verification of commercial systems;
- Development of open path optical systems for detecting elevated CO_2 in the atmosphere,
- Demonstration of the application of NPL's differential absorption lidar system to the quantification of CO_2 plumes, and;
- Development of a European reference method for the direct measurement of CO_2 in emission ducts. Such direct measurement approaches could be used for online monitoring/process control of the capture efficiency.

NPL also have expertise in the monitoring of pollutants associated with carbon capture processes such as nitrosamines.

To find out more about NPL's environmental monitoring work, visit our website.

[28] https://www.gov.uk/guidance/best-available-techniques-environmental-permits

5.2 Regulations and standards

As the potential for CCUS continues to be investigated in the UK and wider, regulatory and standards bodies are developing guidance in line with its wide-scale future deployment. At the present time, the UK abides by EU directives for CCUS and it remains unclear whether these will be readopted or altered once the UK departs from the EU as of 2021. Pertaining to UK activity, current regulations for the storage of CO_2 includes:

- 'Article 6 amendment to the London Protocol'[29], which allows for the transboundary export of CO_2 for offshore geological storage;
- The 'Energy Act 2008'[30], which provides for a licensing regime that governs the offshore storage of CO_2;
- 'EU Directive 2009/31/EC: Geological Storage of Carbon Dioxide'[31] which forms the framework for environmental regulation of CCS across EU Member States, and;
- The 'Storage of Carbon Dioxide Regulations 2010 (SI 2010/2221)'[32], which transposes many of the other requirements of the EU Directive.

Although CO_2 is 'not currently defined as a dangerous substance under the Control of Major Accident Hazards Regulations 1999 (COMAH)[33] or as a dangerous fluid under the Pipelines Safety Regulations 1996 (PSR)'[34], the Health and Safety Executive (HSE) in the UK have stated that modelling releases and dispersion issues along with other technical challenges for CCUS will require further research and validation [73]. Additionally, where EOR is undertaken as part of the CO_2 storage process, a safety case would need to be submitted to the HSE under the 'Offshore Installations (Safety Case) Regulations 1995 (OSCR)'[35].

In relation to standards, ISO Technical Committee (TC) 265 for 'Carbon dioxide capture, transportation, and geological storage' are working on the standardisation of 'design, construction, operation, environmental planning and management, risk management, quantification, monitoring and verification, and related activities in the field of carbon dioxide capture, transportation, and geological storage (CCS)' across its 19 participating country members [74]. British Standards Institution (BSI) committee 'PSE/265 - Carbon Capture Transportation and Storage' are responsible for the UK's input into ISO/TC 265 as well as the UK national standardisation for CCS [75]. It is clear from the needs and challenges outlined in previous chapters that the quality standards of the CO_2 itself will be important; impurities present in the CO_2 can 'reduce process efficiencies, damage equipment/piping and produce hazardous environments where leaks may occur', and therefore guidance – collaboratively developed by experts including NPL – will be essential for UK CCUS plants [23].

5.3 Measurement needs and challenges for carbon storage

The potential challenges surrounding long term CO_2 storage are evident, and it will require robust measurements to ensure the efficiency of the CCUS process and to validate emission reduction claims as we move towards reaching a net zero economy in the UK. The storage of gas is a well understood process in the UK due to a dependence on natural gas as an energy source, however the replacement of these reserves with captured CO_2 brings with it new needs and challenges, including understanding the behaviour of the gas in storage, ongoing monitoring for leak detection and assurance of the longevity of the store.

[29] https://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Pages/LDC-LC-LP.aspx
[30] https://www.legislation.gov.uk/id/ukpga/2008/32
[31] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0031
[32] https://www.legislation.gov.uk/uksi/2010/2221/crossheading/general/made
[33] https://www.hse.gov.uk/comah/
[34] https://www.hse.gov.uk/pubns/books/l82.htm
[35] https://books.hse.gov.uk/bookstore.asp?ACTION=BOOK&PRODUCTID=9780717661848

The measurement needs and challenges for CO_2 storage outlined in the box below were identified through stakeholder engagement with CCUS industry experts as well as a comprehensive literature review undertaken by NPL. The highest priority needs for storage as provided by stakeholders have been summarised and presented in Chapter 6 of this report.

Measurement needs and challenges for carbon storage

Developing gas analysis methods and traceable Primary Reference Materials to enable monitoring of impurities which could result in toxic leaks or reactive atmospheres within storage

Improving the understanding and validation of dispersion models for emitted CO_2 including plume migration, to support safety assessment and the use of measurement approaches which rely on dispersion models to calculate mass emission rates

Development of monitoring methods for sub-sea and sub-surface storage leak detection to quantify losses and avoid potentially harmful releases

Developing technologies capable of online detection of CO_2 leakage to the atmosphere from onshore installations, to ensure the containment of stored CO_2

Validating flow metering for process control to monitor storage capacity

Utilising satellite data to monitor surface deformation and identify large-scale CO_2 leaks

Enabling purity measurements of liquid CO_2 stored in a sub-sea environment

Assessing integrity of well metallurgy in the presence of CO_2 and impurities

Demonstrating reservoir caprock integrity at elevated pressure

Improving the understanding of movement of CO_2 sub-surface plumes along fault zones and CO_2 migration along geologic formations through research programmes, to inform planning of geological storage

Monitoring the dispersion of injected CO_2 into gas reservoirs and other storage mechanisms including any accumulation

Assessing the integrity of CO_2 injection or reservoir monitoring wells

Modelling and monitoring the longevity of carbon storage techniques and accurately measuring the conditions under which it is stored

6 Measurement needs and challenges

The National Physical Laboratory (NPL) and TÜV SÜD National Engineering Laboratory (NEL) hosted a series of three webinars from 6-8 October 2020 focusing on CCUS. The aim of this webinar series was to invite stakeholders from across academia, industry and government to identify, discuss and prioritise crucial measurement needs to support the deployment of CCS technologies alongside the potential to utilise the captured carbon (CCU). Within Annex 1, there is a combined table of all needs and challenges identified throughout the stakeholder engagement and literature review processes across the themes of capture, transport, usage, storage and including those that are cross-cutting. During each session, attendees were requested to input into a form to gain stakeholder insight into the prioritisation of measurement needs related to the session theme. Attendees were asked to rank each measurement need or challenge by ‘high’, ‘medium’, ‘low’ or ‘not relevant’ based on their organisations’ interests. The stakeholders that contributed to these measurement needs and challenges are listed in Annex 2 and the forms used for during our stakeholder engagement webinars can be found in Annex 3. The forms also allowed for attendees to contribute any needs or challenges that they felt were missing or not covered during the event or in the form which have been captured in Annex 1. The highest priority needs and challenges identified through this process have been outlined in section 6.1.

6.1 High priority needs and challenges for CCUS

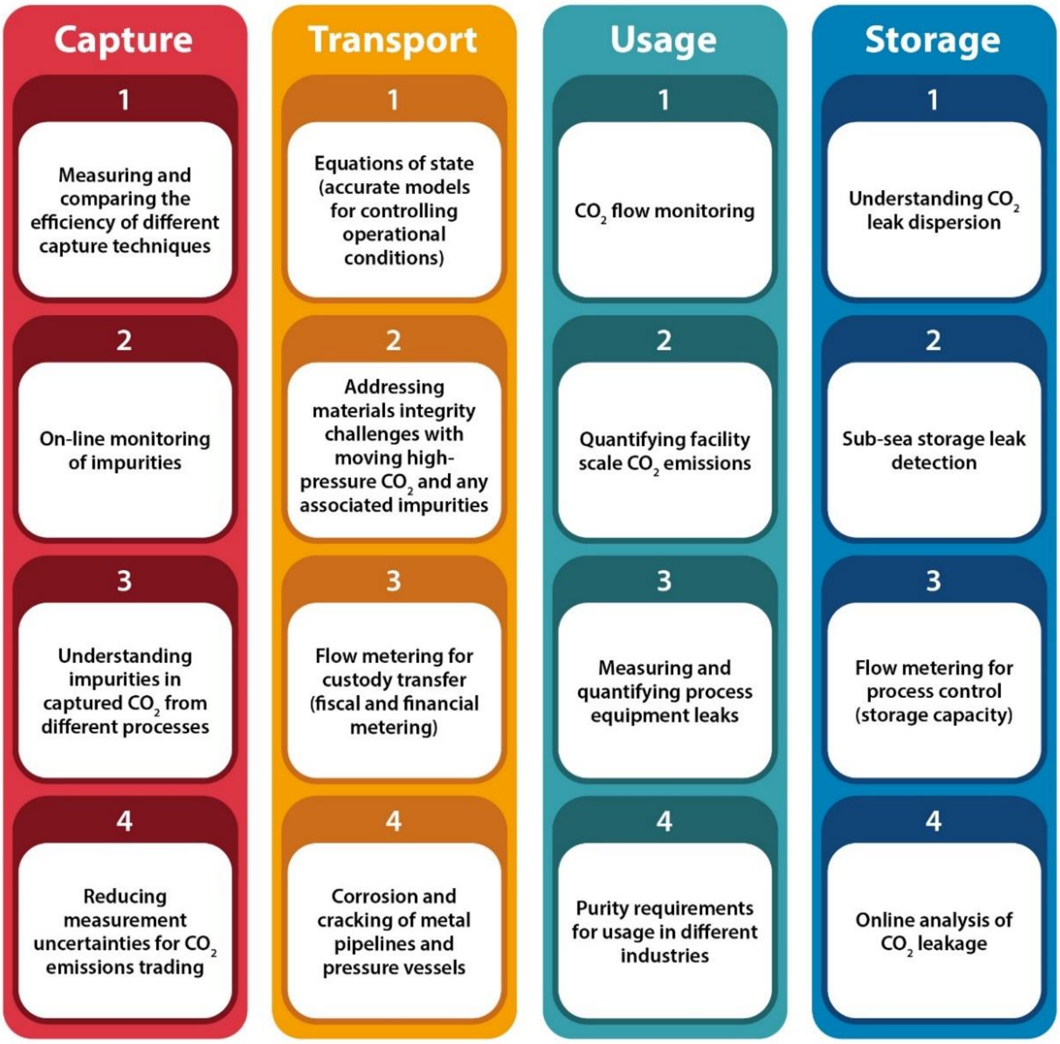

Figure 3: High priority measurement needs and challenges for CCUS

National Engineering Laboratory service capabilities for CCS

As the UK's Designated Institute for Flow and Liquid Density Measurement, NEL has extensive expertise to support the implementation of CCS.

Through multidisciplinary collaboration and innovation, our scientists and engineers are supporting industry to enable accurate measurement for a zero-carbon future.

Examples of relevant NEL capability include:

- Physical properties and phase behaviour;
- The primary standards authority for liquid density measurement in the UK, and;
- Experts in equations of state and physical properties modelling (PPDS) allows us to examine the effects of contaminants on the thermodynamics of CO_2 streams, in terms of density, speed-of-sound, phase envelopes and compressibility, for example.

Flow Measurement

- The primary standards authority for liquid and gas flow measurement in the UK;
- CCS flow meter testing and calibration;
- Provide support on all flow measurement needs for CCS, including meter selection, FEED studies for CCS metering stations; support with regulatory monitoring and reporting compliance; measurement uncertainty analysis and the development of flow measurement tools and reporting templates, and;
- Testing of sensors and other equipment that requires use of a CO_2 flow loop.

Dispersion Modelling and Process Modelling

- CFD modelling of CO_2 pipelines at all stages of CCS, including complex leakage scenarios, topography and flow meter performance;
- Modelling of supercritical fluids;
- Modelling of processes including estimating additional flow restrictions caused by closed stacks, heat loss through pipelines and CO_2 behaviour at the well head, and;
- Dispersion modelling of leaked CO_2.

Pipeline Packing Estimating and Allocation Measurement

- Developing algorithms and undertaking calculations to support stock variation in CCS pipelines, and;
- Allocation modelling to support fiscal measurement and product yield in shared pipeline infrastructure.

To find out more about NEL, please visit their website.

Annex 1: Summary of all measurement needs and challenges identified for CCUS

Theme	Measurement challenge	Description
Capture	Process	**Undertaking real-time measurement of post-capture emissions** to enable process control during capture and report emitted substances for example oxides of nitrogen
		Developing pre-capture flue gas analysis to identify any substances that may impact on solvent performance
		Identifying and quantifying new pollutant emissions caused by capture to reduce unintended consequences of CCUS deployment for example amines and nitrosamines including aerosols
		Understanding the potential impact of CCUS capture processes on ambient air, for example atmospheric chemistry of amines and nitrosamines, and determining background levels
	Purity	**Understanding the effect of capture processes** on measurement techniques used for reporting regulated pollutants and define reference conditions for example oxygen and CO_2 to ensure continued compliance
		Understanding impurities in captured CO_2 to identify whether a purification step is required to meet technical specifications including cross-reactions between impurities from different processes
		Undertaking validation of analytical instruments used to perform on-line monitoring of impurities to indicate degradation of the capture solvent and general indication of capture performance
		Understanding the breakdown products of new solvents as they may impact the purity of captured CO_2 or lead to pollutant emissions

	Trade	**Reducing measurement uncertainties for CO_2 emissions trading** to ensure compliance with UK and international regulations
	Standards	**Supporting standardisation activities** for carbon capture
	Efficiency	**Measuring and comparing the efficiency of different capture techniques and configurations** to provide confidence in investments into technologies in support of CCUS business cases including full lifecycle analysis and direct measurements
	Instruments	**Characterisation and calibration of humidity-measuring instruments** for process conditions, to compensate effects of background CO_2 and high pressure
Transport	Purity	**Assessing the impact of impurities** on the corrosivity of CO_2 at high pressure
		Developing gas metrology infrastructure to support purity measurements
		Developing a purity specification including amount fraction thresholds for key impurities
	Process	**Improving equations of state** to support the development of accurate models used for controlling operational conditions
		Improving the accuracy of flow metering used for custody transfer to enable fiscal and financial metering including at high pressure
	Corrosion	**Assessing of integrity of containment materials** in the presence of high pressure CO_2 to avoid corrosion and cracking of pipelines
		Developing standard test methods for corrosion and cracking of pipelines and pressure vessels
	Leakage	**Developing and validating techniques for pipeline leak detection** to be able to efficiently monitor and locate leaks along pipelines

		Producing methods for component level CO_2 leak detection and quantification using technologies such as sniffing and optical gas imaging
	Infrastructure	**Assessment of the potential for reusing existing pipelines** to reduce decommissioning costs and stranded assets as a result of the energy transition
Usage	Purity	**Establishing purity requirements for CO_2 usage in different industries** including the supporting metrology infrastructure
	Leakage	**Developing and validating methods for detecting and quantifying leaks of CO_2 from CO_2 plants,** downstream of the supply, including process equipment and piping leaks, to support leak detection and repair
		Developing standardised methods for quantifying facility scale CO_2 emissions to enable reporting under regulations
	Flow	**Improving CO_2 flow monitoring** to support process control
	Life cycle	**Performing a life cycle assessment** including whether the CO_2 eventually enters the atmosphere or is permanently stored
Storage	Physical properties, impacts and processes	**Assessing integrity of well metallurgy** in the presence of CO_2 and impurities
		Demonstrating reservoir caprock integrity at elevated pressure
		Assessing the integrity of CO_2 injection or reservoir monitoring wells
		Monitoring the dispersion of injected CO_2 into gas reservoirs and other storage mechanisms including any accumulation
		Assessing the integrity of CO_2 injection or reservoir monitoring wells

		Modelling and monitoring the longevity of carbon storage techniques and accurately measuring the conditions under which it is stored
	Purity	**Developing gas analysis methods and traceable Primary Reference Materials** to enable monitoring of impurities which could result in toxic leaks or reactive atmospheres within storage
		Enabling purity measurements of liquid CO_2 stored in a sub-sea environment
	Leakage	**Improving the understanding and validation of dispersion models** for emitted CO_2 including plume migration, to support safety assessment and the use of measurement approaches which rely on dispersion models to calculated mass emission rates
		Development of monitoring methods for sub-sea and sub-surface storage leak detection to quantify losses and avoid potentially harmful releases
		Developing technologies capable of online detection of CO_2 leakage to the atmosphere from onshore installations, to ensure the containment of stored CO_2
		Utilising satellite data to monitor surface deformation and identify large-scale CO_2 leaks
		Improving the understanding of movement of CO_2 sub-surface plumes along fault zones and CO_2 migration along geologic formations through research programmes, to inform planning of geological storage
	Flow	**Validating flow metering for process control** to monitor storage capacity
Cross-cutting	Systems approach	**Modelling of whole system approaches and life cycle analysis** of energy use and processes

Annex 2: Contributors

National Physical Laboratory

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External

Accord Energy Solutions
Air Liquide
Aker Carbon Capture
Aker Solutions
Anglia Ruskin University
BEIS
Blacktent Consultancy
C-Capture
CCSA
Centre for Renewable Energy Sources and Saving
Costain
DNV GL
Energy Geoscience
Eni UK
Equinor
Geostock Group
Health and Safety Executive
Heriot-Watt University
IEAGHG
Imperial College London
Intellectual Property Office
ITPEnergised
Materials Processing Institute
McDermott
National Grid
NECCUS
Pace Flow Assurance
Pale Blue Dot Energy
PMW Technology
Qatar Petroleum
Rural Payment Agency
Silixa
SSE
Technology Centre Mongstad
Thornfield Technical Solutions
TÜV SÜD National Engineering Laboratory
Unisensor
University of Birmingham
University of Chester
University of Liverpool
Yokogawa

Annex 3: Stakeholder insight forms

NPL-NEL CCUS webinar series - Capture

Please respond to the questions below for the session Tuesday 6th October 2020

1. Please provide your name and company

Enter your answer

2. Please select whether the measurement challenges/needs listed below are of 'high', 'medium', 'low' priority or 'not relevant' to your organisation.

	High	Medium	Low	Not relevant
Reducing measurement uncertainties for CO2 emissions trading	○	○	○	○
Measuring/comparing the efficiency of different capture techniques	○	○	○	○
Real-time measurement of emissions to enable process control	○	○	○	○
Identifying new pollutant emissions caused by capture	○	○	○	○
Effect of capture processes on measuring and reporting regulated pollutants	○	○	○	○
Accurate flow metering from CO2 capture to storage	○	○	○	○
Understanding impurities in captured CO2 from different processes	○	○	○	○
On-line monitoring of impurities	○	○	○	○

3. Are there any measurement needs or challenges for carbon capture that you feel are missing from the table above? If so, please include here.

Enter your answer

Submit

NPL-NEL CCUS webinar series - Transport and Storage

Please respond to the questions below for the session Wednesday 7th October 2020

1. Please provide your name and company

Enter your answer

2. Please select whether the measurement challenges/needs listed below are of 'high', 'medium', 'low' priority or 'not relevant' to your organisation.

	High	Medium	Low	Not relevant
Materials integrity challenges with moving high-pressure CO2 and impurities				
Corrosion and cracking of metal pipelines and pressure vessels				
Equations of state (accurate models for controlling operational conditions)				
Understanding CO2 leak dispersion				
Assessing the impact of impurity on the corrosivity of CO2 at high pressure				
Sub-sea storage leak detection				
Online analysis of CO2 leakage				
Flow metering for process control (storage capacity)				
Enhanced oil recovery				
Purity measurements (reactivity, harmful impurities in leaks)				
Satellite surface deformation				
Pipeline leak detection				
Understanding / validating dispersion models for released CO2				
Component level CO2 leak detection/ quantification - sniffing, optical gas imaging				
Flow metering for custody transfer (fiscal and financial metering)				

3. Are there any measurement needs or challenges for carbon transport and storage that you feel are missing from the table above? If so, please include below.

Enter your answer

Submit

NPL-NEL CCUS webinar series - Usage

Please respond to the questions below for the session Thursday 8th October 2020

1. Please provide your name and company

Enter your answer

2. Please select whether the measurement challenges/needs listed below are of 'high', 'medium', 'low' priority or 'not relevant' to your organisation.

	High	Medium	Low	Not relevant
Purity requirements for usage in different industries	○	○	○	○
Measuring and quantifying process equipment leaks	○	○	○	○
CO2 flow monitoring	○	○	○	○
Process control including real time measurements	○	○	○	○
Quantifying facility scale CO2 emissions	○	○	○	○

3. Are there any measurement needs or challenges for carbon usage that you feel are missing from the table above? If so, please include below.

Enter your answer

Submit

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