CHALLENGES RELATED TO CARBON TRANSPORTATION AND STORAGE – SHOWSTOPPERS FOR CCS?

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INTRODUCTION

As two of the authors have described in previous work, carbon capture and sequestration (CCS) technologies can become an important tool in a wider carbon mitigation portfolio in the coming decades.[1] That earlier study concentrated mostly on challenges related to capturing carbon, with a special focus on the United States (U.S.). However, transportation and storage infrastructure is required to remove CO_2 captured from power plants and industrial installations, and to inject the CO_2 into deep saline geological formations or depleted oil and gas fields for permanent sequestration. Transportation can be undertaken using pipelines or (if in an offshore environment) ships, and storage facilities are analogous to those used for temporary or seasonal natural gas storage. The U.S. has a substantial network of CO_2 pipelines and injection facilities that has been developed over four decades for use in oil production in a process known as enhanced oil recovery (EOR). Unlike the U.S., the European Economic Area (EEA) has not developed such an infrastructure and consequently Europe needs to start from scratch if CCS is to be deployed at scale as a

[1] http://www.brookings.edu/~/media/research/files/papers/2015/10/low-carbon-energy-ccs-banks-boersma/low_carbon_energy_ccs_banks_boersma_final.pdf

decarbonisation tool. Existing European oil and gas transport and production infrastructure does, however, offer some potential for re-use in some limited circumstances.

To meet the aspirations and objectives of the UNFCCC Paris Agreement of 2015, CO_2 transport and storage infrastructure development and operation will be required to service multiple sectors of the economy, and particularly to achieve sustainable industrial regions. The consequence of this is that the infrastructure planning, investment and development will eventually need to progress independently of individual capture projects or CO_2-EOR projects in order to achieve the necessary deployment rates and operational scale. It is also important to understand that each activity within the CCS value chain requires a different set of skills and corporate capability, as well as being subject to a different business proposition[2]. For example, electric utilities do not necessarily have the capability to undertake transport and storage operations, and normally work with different investment risk and return profiles in their business. Hence the commercial interfaces between different organizations in the value chain present new and substantial challenges to operators, financiers, insurers and regulators.

This policy brief examines whether challenges related to transport and storage of carbon dioxide can be showstoppers for commercial CCS, by examining both the cases of the U.S. and Europe. Substantial programs of research, development and demonstration have been pursued in both regions with varying levels of success resulting primarily from different policy objectives, investment conditions, and multiple constituent jurisdictions. We therefore assess both cases separately before drawing conclusions.

RISKS, UNCERTAINTIES AND MARKET BARRIERS ASSOCIATED WITH TRANSPORTATION AND STORAGE OF CO_2

In order for CCS to be an effective climate mitigation tool, "it must be able to contribute to CO_2 emissions reductions on the scale of billions of metric tons per year. Today its contribution is on the scale of millions of metric tons."[3] The sheer volume of CO_2 from a coal fired power plant illustrates this challenge: MIT estimates that a typical 1,000 MW pulverized coal plant, with 90 percent capture, would yield 6.24 million tons/year of CO_2 that need to be transported and permanently stored.[4] Thus, CCS requires that a transportation and long-term geologic storage infrastructure be established and available (and governed by third party access regulations) to handle the billions of tons of CO_2 that will be captured globally from the fleet of fossil fuel-fired plants and carbon intensive industrial installations, assuming the usage of the integrated technology becomes commercially viable. Currently, this scale of infrastructure does not exist.

Capture is about the cost challenge, storage is about the uncertainty challenge

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[2] See for example Esposito RA, Monroe LS, Friedman JS, *Deployment models for commercialized carbon capture and storage.* Environ Sci Technol. 2011 Jan 1;45(1):139-46. doi: 10.1021/es101441a. Epub 2010 Aug 19.

[3] Herzog, H.J., *Scaling up carbon dioxide capture and storage: From megatons to gigatons*, Energy Econ. (2010), doi:10.1016/j.eneco.2010.11.004.

[4] Ibid p 60.

The development of transport and storage infrastructure as a commercial disposal service at such large scale is currently hampered by a number of market failures as well as investment barriers associated with risk and uncertainty. Furthermore, although not an intrinsic risk unique to CCS, negative public attitude to transport and storage can prevent projects from progressing beyond feasibility.[5]

The two principal primary market failures in Europe and the U.S. that have limited private sector appetite to participate in independently building and operating transport and storage infrastructure are the missing market for the services and a co-ordination failure between emitters and storage site developers. The former is simply a reflection of the lack of CO_2 capture projects and no clear visibility of a revenue stream for potential service providers. The latter is the chicken and egg problem resulting from the need for storage certainty to take a Final Investment Decision (FID) for building a capture facility, and the need for CO_2 supply certainty to take FID for building a storage facility. Both of these failures can be mitigated to a limited extent by the EOR utilization business model existing in the U.S., but this is not currently a realistic option in Europe.

Risks and uncertainties fall into three main categories: technical viability, legal and regulatory, and commercial and financing. Technical viability of a storage site is geology dependent with the primary site characteristics being capacity, containment and 'injectivity'. Proving these to a sufficient level of confidence for financing and investment is one of the main issues facing storage development. To some extent technical uncertainties are the common denominator that influences legal, regulatory, commercial and financing risks.

Key to infrastructure developers is the extent to which laws and regulations are sufficiently practical to avoid excessive costs, and to enable rather than hinder commercial and financial structures required to undertake investments, operations, decommissioning and, in the case of storage, permanent site closure. There are currently very few companies that are prepared to be the first movers and solve the contractual and legal complexity arising from the combination of all these risks.

Technical Viability

Before even addressing subsurface risks, location is a key consideration in the development of transportation and storage infrastructure and the associated business model, as it greatly impacts costs. Quite simply, a full chain CCS project will be more expensive if the capture site is far from the storage site and there is no supporting pipeline infrastructure.

The U.S. is fortunate to have an operational CO_2 pipeline network of over 4500 miles established primarily for EOR purposes.[6] While it is estimated that the majority of large CO_2 sources in the U.S. are within 50 miles of a suitable geologic reservoir, not all power plants and industrial installations are located near potential storage sites, and as climate policies are

[5] See for example the Global CCS Institute case study on the Barendrecht project Nov 2010: http://www.globalccsinstitute.com/sites/www.globalccsinstitute.com/files/publications/8172/barendrecht-ccs-project-case-study.pdf

[6] DOE NETL A Review of the CO_2 Pipeline Infrastructure in the U.S., DOE/NETL-2014/1681, April 21, 2015

implemented more pipelines will be needed.[7] Modeling conducted for DOE's recent Quadrennial Energy Review indicated that an average of 1,000 miles per year of additional CO_2 pipelines is required by 2030.[8] Depending on the low carbon scenario, the cost ranges from $330,000 to $560,000 per mile.[9] Thus, to develop and commercialize CCS, expanding the existing CO_2 pipeline infrastructure is required.

Currently, in the U.S. the economics of a CCS power project are better if the capture site is located near an oil and gas reservoir that can use CO_2 for EOR. It is considered most likely that CCS projects initially will be located near existing pipeline infrastructure and oil and gas fields for EOR, and thus a regional infrastructure will emerge first.[10] However, there is a general consensus that for long-term sequestration of large volumes of CO_2 required to meet greenhouse gas reduction targets, the necessary infrastructure is not in place, it is not clear whether and how a national, inter-state pipeline transportation and storage network may evolve, and no private sector entity currently is willing to take on the cost of building it.

Due to a high level of public opposition, CO_2 storage is unlikely to occur onshore in continental Europe, and in the United Kingdom, Netherlands and Norway policy is focused on offshore storage for a variety of reasons including that the North Sea has an active upstream oil and gas industry. Other potential storage regions in Europe include the Baltic Sea, the Adriatic Sea, and the Eastern Mediterranean. Consequently, the deployment of CCS at scale in Europe will be dependent on expensive offshore injection and storage facilities, subsea pipelines and possibly shipping. Infrastructure costs in this environment vary widely and are highly dependent on the network topology that would be built both offshore and onshore.[11] Onshore transport infrastructure will be needed to bring emissions from inland Europe to the coast, and some proposals include barges carrying liquefied CO_2 along major rivers such as the Rhine. The European Commission's Joint Research Centre has suggested that 20,374 km (12,733 miles) of pipelines and cumulative investment of €29 billion by 2050 is required to satisfy Europe's climate objectives.[12] This infrastructure build-out is a similar order of magnitude to that required in the U.S. by 2030, but at a much higher cost.

Technical viability of a storage site is assessed through a process known as site characterization. This process uses techniques and technologies from the oil and gas exploration and production industry to determine how large a site is (capacity), whether it can keep CO_2 permanently sequestered (containment), and at what rates CO_2 can be injected over the proposed operational life of the site. Depending on the nature of the site and its geology, characterization can take from a few years to a decade or more. Operating oil and gas fields require the least effort, whereas characterizing a large saline formation that has not been

[7] Dooley et al
[8] QER – p 7-25
[9] Ibid
[10] FROM MIT 2007, p.
[11] Zero Emissions Platform reports on Transport and Storage costs 2011 available here: http://www.zeroemissionsplatform.eu/library/publication/168-zep-cost-report-storage.html
[12] Joint Research Centre (JRC) *The evolution of the extent and the investment requirements of a trans-European CO_2 transport network*, 2010: http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/15100/1/ldna24565enn.pdf

explored for oil and gas requires a much larger effort and cost. Nevertheless 'discovering' a very large high quality saline formation has the economic benefits of a single location for large volumes, one access transport route and ease of expansion.

Consequently, CO_2 storage projects should be considered in two distinct periods: one for the characterisation and other development work prior to FID and one for the construction and operation post FID. These have significantly different financial risk profiles. In the absence of a market for storage services or supporting policies, there is no visibility on revenues and returns, and hence no incentive to undertake storage characterisation that does not have a known or guaranteed outcome.

The objective of the pre-FID characterization period is to understand and reduce technical uncertainties relating to the behavior of CO_2 once injected at significant volumes, i.e. well beyond the levels injected thus far in site characterizations and testing (at 1 million metric tons per year), as well as in the oil and gas industry under commercial conditions (e.g. similar storage rates at Sleipner[13] in Norway and Weyburn in Canada).

A utility or project developer will not take on this kind of pre-FID risk. While CO_2 for EOR may provide a short- to medium-term use for captured carbon, long-term permanent storage in saline formations represents a major infrastructure challenge for CCS deployment if left solely to the private sector and market forces.

Legal and regulatory risk

Building the requisite transportation and storage infrastructure is closely linked to legal and regulatory risks: establishing a stable, transparent, and predictable legal and regulatory framework under which facilities will operate, is critical for creating a sustainable business model that can enable private sector investment in both capture and infrastructure projects alike.

For CO_2 pipeline transportation, there are regulatory uncertainties in both the U.S. and Europe, each with their own nuances, revolving around siting and permitting, rate setting and cost recovery, jurisdictional oversight, CO_2 classification, common carrier status, third party access and eminent domain.[14] While some U.S. states have started to address these issues, they remain unresolved at the federal level.[15] In Europe, access and permitting regimes are left to individual countries, although some over-arching principles (such as third party access and environmental impact) are contained in European Directives. Those European countries with mature oil and gas sectors and regulation of pipeline infrastructure and operations are better placed to facilitate rapid deployment of infrastructure than those without the regulations and experience. The offshore storage solution in Europe also requires the ability to transport CO_2 across borders in international waters. Currently this is prevented because

[13] Sleipner is a gas field offshore Norway where both capture and injection have been taking place since 1996
[14] World Resources Institute. "CCS Guidelines: Guidelines for Carbon Dioxide Capture, Transport, and Storage." Washington, DC, 2008, p. 22 (WRI Guidelines 2008). See also "Carbon Capture and Sequestration (CCS)," Congressional Research Service, June 19, 2009.
[15] An additional complicating legal factor in the U.S. is that mineral rights and surface rights may be severed in some states, i.e., property owners with surface rights may not own resources below the surface.

the amendment to the London Protocol to the Convention on the Prevention of Marine Pollution that will allow these activities has not yet been ratified.[16] Sorting out these challenges will be critical in order to reduce the commercial risk for project developers. As noted by one U.S. company participating in our research, it is spending far more time and manpower on pipeline development than anticipated, largely revolving around navigating private rights of way.

The technical risks and uncertainties associated with long-term, permanent geologic storage of CO_2 have led to new, and in some cases major, legal and regulatory challenges to ensure appropriate governance for environmental and human health reasons while at the same time striking a balance with operational feasibility without excessive cost. New and sometimes unclear laws pose risks to developers and financiers. Furthermore, civil liability and emissions trading liability are two additional areas of law that interact with the administrative liabilities that are being handled through regulatory development.[17]

The three main areas of regulatory development that have been, or are being, addressed in jurisdictions around the world are:[18]

- Legal access to pore space (*property* rights, mineral rights);
- Rules on *permitting* underground injection; and
- Long-term stewardship (*liability*, monitoring & verification).

In the U.S., federal and state law largely assigns property owners with mineral rights, but does not address pore space to store CO_2. A legal framework is required to guide the process of assigning or acquiring pore space rights. European jurisdictions tend not to assign mineral rights to property owners and, in the case of offshore storage in either the territorial sea or the continental shelf, countries manage the pore space via public authorities.

The U.S. EPA has implemented rules governing CO_2 injection and reporting, but they do not address the other gaps in the overall regulatory framework mentioned here. Some oil and gas operators off taking CO_2 for EOR have expressed concerns that they pose overly complex requirements for CCS projects. However, other EOR operators have fully embraced the rules and have negotiated and received permits under the EPA framework.

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[16] Globally, international cooperation is needed to accommodate cross-border pipeline networks. For instance, the London Protocol of 1996 still prohibits the trans-boundary transportation of CO_2 to offshore geological storage sites and is awaiting ratification. Such regional agreements can foster shared, integrated CO2 pipeline networks reducing infrastructure costs for operators. See International Energy Agency, *Technology Roadmap: Carbon Capture and Storage*, by Ellina Levina et al. Paris: OECD/IEA, 2013, available here: http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf
and the IEA report *Carbon Capture and Storage and the London Protocol* available here: https://www.iea.org/publications/freepublications/publication/CCS_London_Protocol.pdf

[17] Havercroft, I. and Macrory, R., *Legal Liability and Carbon Capture and Storage*, GCCSI and UCL, October 2014, available here: http://blogs.ucl.ac.uk/law-environment/files/2015/05/legal-liability-carbon-capture-storage-comparative-perspective.pdf

[18] Herzog, H.J., *Scaling up carbon dioxide capture and storage: From megatons to gigatons*, Energy Econ. (2010), doi:10.1016/j.eneco.2010.11.004

European member states govern CO_2 storage under domestic laws and regulations that implement the European Directive on the Geological Storage of Carbon Dioxide.[19] This Directive underwent a rigorous evaluation during 2014 with substantial stakeholder consultation and input. The conclusion of the review was that a lack of practical experience in applying the Directive meant any significant changes would be counterproductive[20], however issues raised by projects attempting to move beyond feasibility should inform some revisions by 2020. At the time of writing only one storage permit has been granted under this regime, and that for a project in the Netherlands.

Regulatory handling of long-term liability is often considered to be the most significant risk to storage developers[21]. This revolves around defining who is responsible for overseeing storage of CO_2 once a site is closed, rules governing when that responsibility is taken on, how monitoring, verification, and reporting are conducted, who is responsible for CO_2 (or associated damages) should it leak, and how these activities are funded. Europe is an excellent example where a rigorous regulatory regime is in place, but developers see a substantial risk exposure that derives not so much from the operations themselves but the front loading of contingent liabilities resulting from future (low likelihood) leakage events. This is exacerbated by the linkage of the storage liability with the European Trading Scheme: the unknown future value of a metric ton of CO_2 that has leaked is equated to an EU allowance on the carbon market that has been cancelled when stored from a capture facility.

An important issue related to legal and regulatory risk is public acceptance. While Europe has experienced direct opposition to CO_2 storage, U.S. EOR operations have not. Nevertheless, as large scale underground injection activities in the U.S. move away from existing fields into new areas and new types of operations, heightened awareness of local communities will require proactive management for public acceptance. Failure to address the public's perceptions and concerns may compound the risks confronting CCS projects.

Commercial and Financing Risk

As is typical in business ventures, technical, legal and regulatory uncertainties have to be handled through commercial arrangements between different parties participating in the constituent activities. CO_2 transport and storage infrastructure for the sole purpose of removing and disposing of carbon dioxide emissions is an entirely new business proposition with a profile of counterparty risk that deals in carbon penalties and leakage liabilities rather than in value adding to fungible commodities. Unlike the CO_2-EOR business model, wherein the CO_2 is commoditized and known commercial structures are applied for transportation and delivery performance between source supplier and oil field customer, transportation and storage as a disposal service is subject to entirely different business and investment risks deriving from the technical and legal issues described above.

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[19] Directive 2009/31/EC of The European Parliament and of The Council on the geological storage of carbon dioxide, April 2009

[20] European Commission, Support to the review of Directive 2009/31/EC on the geological storage of carbon dioxide (CCS Directive), December 2014

[21] Faure, M., *Liability and Compensation for Damage Resulting from CO2 Storage Sites*, 40 Wm. & Mary Envtl. L. & Pol'y Rev. 387 (2016), http://scholarship.law.wm.edu/wmelpr/vol40/iss2/3

There is currently a dearth of practical experience of commercial and financing structures that can work in a full CCS chain situation where transport and storage are each handled as service businesses to a CO_2 source emitter. The most advanced attempt at such structures has occurred in the UK's CCS commercialization program, but even this was a special case in the context of a government procurement exercise consisting of a capital grant and contract-for difference feed-in-tariff.[22]

Perceptions of the future of CO_2 transport and storage policy and supporting frameworks, including climate targets and public sector involvement, are also adding to the technical and legal risks for potential transport and storage developers. Hence, a number of interrelated commercial and financial risks currently exist that must be overcome if transport and storage as a service is to become a viable business proposition:[23]

- Storage is not financeable/investible (*capital market limitations*);
- Construction and performance risk (*intra-chain risk*);
- Sovereign/policy risk (*change of law risk*).

Capital investments in transport and storage can each run into several hundred million dollars, with offshore storage site development potentially costing up to $750 million. The economic life of storage facilities can be over 20 years (with facilities possibly in place for another 20 years after injection ends), and transmission or network trunk pipelines as much as 50-60 years. Ensuring stability of income and returns on these assets therefore requires a sustained robust joint regulatory and contractual framework that can adapt to changes in circumstances and that addresses the following:

- Avoiding stranded asset (white elephant) risk by coordination of CO_2 supply and demand, from capture and storage respectively;
- Reducing or removing the exposure to risks of one part of the CCS chain to failures/underperformance elsewhere in the chain;
- Capping or limiting liabilities for key storage performance characteristics and for certain categories of leakage;
- Developing a basis for allocation of CO_2 storage specific risks and liabilities between industry and the public sector; and
- Mitigating exposure to higher costs or lower revenues due to changes in law for matters specific to CCS/CO_2 storage.

Taken together all of these risks and uncertainties contribute to the coordination market failure described earlier, posing considerable difficulty for a utility or project developer considering building a CO_2 capture project. Private companies need some mechanism or policy approach that addresses or shares the risks involved if they invest in a capture project and there is no way to dispose of the CO_2, i.e., a storage site does not get built, the storage site gets shut in, or there is some other commercial or infrastructure related issue that

[22] UK Government CCS Commercialization Programme ITPD (Invitation to Participate in Discussions) 2012
[23] The Crown Estate and Deloitte, *A need unsatisfied: Blueprint for enabling investment in CO_2 storage*, February 2016

interrupts or precludes the company from providing the CO_2 to an off-taker. This risk is more acute when there is a carbon price mechanism in place.

POLICY AND REGULATORY FRAMEWORKS IN THE U.S. AND EUROPE[24]

United States - Existing Policies and Regulations

U.S. government CCS policy in CO_2 transportation and storage has focused mainly on permitting, testing and site characterization for geologic sequestration, while at the state level, more than a dozen states have established a variety of regulations and laws in support of CO2 pipeline transportation and geologic sequestration.[25]

Geologic Storage RD&D

DOE's carbon storage RD&D program goals are summarized below:[26]

- Develop and validate technologies to ensure for 99 percent storage permanence.
- Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.
- Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- Develop Best Practice Manuals (BPMs) for monitoring, verification, accounting (MVA), and assessment; site screening, selection, and initial characterization; public outreach; well management activities; and risk analysis and simulation.

The National Energy Technology Lab (NETL) indicates that there are currently 70 carbon storage R&D projects from the laboratory/bench scale through pilot stages.[27] Most of the carbon storage funding – 65-70 percent in recent years – goes to supporting seven Regional Carbon Sequestration Partnerships (RCSPs). The RCSPs are public-private cooperative arrangements designed "to determine the best geologic storage approaches and apply technologies to safely and permanently store CO_2 for their specific regions." The status of active RCSP projects is summarized in **Table 1**.

There are also smaller scale research and pilot projects in geologic storage supported by the DOE. [28]

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[24] For an elaborate overview of legal and regulatory developments related to CCS, we refer to Dixon, T. et al. (2015). Legal and Regulatory Developments on CCS. International Journal of Greenhouse Gas Control, 40, 431 – 448.

[25] To better appreciate 'U.S. government' in this context: in short DOE leads a number of CCS research and development programs to facilitate the commercial deployment of CCS; EPA's aim is to guarantee that geologic sequestration is done safely; and the Department of Transportation regulates pipelines. In addition, states issue rules to meet federal requirements related to CCS, but also develop their own policies and regulations governing facilities within their jurisdiction.

[26] NETL, "Carbon Storage Technology Program Plan, December 2014," p 19.

[27] NETL 2014, table 4.

[28] See NETL at http://www.netl.doe.gov/research/coal/carbon-storage/carbon-storage-infrastructure.

Table 1

Regional Carbon Sequestration Partnership (RCSP)
Status of Large-Scale Development Phase Projects

Name	CO_2 Source	Project Type	Total Storage Goal (tonnes of CO_2)	Stored to date (tonnes of CO_2)
Big Sky Carbon Sequestration Partnership – Kevin Dome Project	Natural	Saline storage	1,000,000	0
Midwest Geological Sequestration Consortium – Illinois Basin Decatur Project	Ethanol Plant	Saline storage	1,000,000	999,215
Midwest Regional Carbon Sequestration Partnership – Michigan Basin Project	Natural Gas Processing	EOR	1,000,000	596,282
Plains CO_2 Reduction Partnership – Bell Creek Field Project	Natural Gas Processing	EOR	1,000,000	2,982,000
Southeast Regional Carbon Sequestration Partnership – Citronelle Project	Natural	Saline storage	Up to 300,000	114,104
Southeast Regional Carbon Sequestration Partnership – Cranfield Project	Coal Power	Saline storage	5,000,000	4,743,898
Southwest Regional Carbon Sequestration Partnership – Farnsworth Unit – Ochiltree Project	Ethanol & Fertilizer	EOR	1,000,000	490,720

Source: NETL data as of September 2016.

Geologic Storage Regulation

As noted, the legal and regulatory framework for geologic storage revolves around three key issues: permitting, access to pore space, and long-term liability and stewardship.

The U.S. government has taken steps to address permitting issues. In 2010 the EPA created a new class of wells to be regulated under its existing Underground Injection Control (UIC) program, which is designed to protect underground sources of drinking water: a Class VI well for long term sequestration of CO_2. Class VI permits have been issued for FutureGen in Illinois (prior to its cancelation) and the Decatur project run by Archer Daniels Midland. The UIC's regulations can be implemented either by EPA or states may apply to have primary regulatory authority. Thus far, North Dakota is the only state to apply for "primacy", under which the state would administer the class VI permitting program instead of the EPA.[29]

The UIC Class VI regulation specifies that if a company currently operating under a Class II permit to inject CO_2 for EOR wants to begin injecting CO_2 for long term storage, it does not have to apply for a separate Class VI permit, unless there is an increased risk to underground sources of drinking water.[30] In April 2015 the EPA Office of Ground Water and Drinking Water released a clarification that eased the requirements of Class II operators, and encouraged states "to apply for primacy for all well classes", and confirmed that Class II wells used in storage through EOR do not necessarily require a Class VI permit.[31] The EPA's UIC regulation, however, does not address access to pore space or long term liability and stewardship; the main goal is the protection of drinking water. Some of these issues are addressed at the state level.

Included in the issue of long-term stewardship of sequestered CO_2 is monitoring and reporting requirements. Currently under the EPA's *Mandatory Reporting for Greenhouse Gasses Rule*, facilities injecting CO_2 for EOR or long-term sequestration must provide information on that activity, i.e., the main purpose is monitoring and reporting, not to require the control of injected GHGs.[32]

States have also implemented policies and regulations to address key issues in geologic sequestration, including liability, pore space ownership, ownership of CO_2, establishment of storage funds, and approaches to unitization.[33] Even though there is more to be said about the details of those various policies and regulations, these fall outside the scope of this paper.

CO_2 Pipeline Transportation Regulation

CO_2 pipeline safety is regulated at the federal level by the Department of Transportation (DOT). Specifically, the Pipeline and Hazardous Materials Safety Administration (PHMSA) oversees the design, construction, operation and maintenance, and spill response planning.[34]

However, regulations and oversight related to siting, economic regulation (setting of rates), and access are not specified under in the current federal legal framework. In effect, existing laws have largely been developed and implemented before serious consideration of CCS to reduce GHG emissions, and specifically transporting CO_2 over long distances for permanent geologic storage. Both FERC and the Surface Transportation Safety Board under DOT have interpreted their respective mandates to *not* include CO_2 (with the exception of pipelines on

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[29] NCC, Fossil Forward, p 107.
[30] https://www.gpo.gov/fdsys/pkg/FR-2010-12-10/pdf/2010-29954.pdf - page 77244 and further.
[31] http://water.epa.gov/type/groundwater/uic/class6/upload/class2eorclass6memo.pdf
[32] http://www.ecfr.gov/cgi-bin/text-idx?SID=2f0c32ce3386dc0f7e735fd9c70a1771&mc=true&node=pt40.21.98&rgn=div5
[33] "Regulation for Underground Storage of CO2 Passed by U.S. States," Holly Javedan, Massachusetts Institute of Technology, 2015.
[34] http://www.ecfr.gov/cgi-bin/text-idx?SID=218b7621fc7e24b6f6c37946ae63f3d9&mc=true&node=pt49.3.195&rgn=div5#se49.3.195_10

federal lands in which case the Bureau of Land Management in the Department of Interior has jurisdiction).

Many states also regulate various aspects of CO_2 pipelines, in particular those with long-standing EOR operations. For example, Texas and New Mexico have CO_2 pipeline regulations governing safety, siting, and eminent domain, and North Dakota and Montana have assigned common carrier status to CO_2 pipelines.[35]

United States - Gaps and Weaknesses

The principal challenge in the U.S. is a lack of progress in addressing infrastructure, and legal and regulatory risks in both transportation and storage. In short, there is no comprehensive policy in place at the federal level to address infrastructure, and legal and regulatory risks. In effect, there is a market failure around who will pay for – and who will build – the infrastructure, and the legal and regulatory framework to support the required infrastructure development is not in place.

There is no overarching federal regulatory framework governing CO_2 pipelines regarding, rates, access, or siting authority, and these gaps will affect project development and economics. For example, rates may be set differently for existing pipelines carrying CO_2 as a commodity for use in EOR as opposed to new pipelines dedicated for CO_2 disposal.[36] As the pipeline network expands to accommodate more movement of CO_2 across states, it will be important to ensure that rules governing non-discriminatory access and eminent domain are in place.[37] While states currently address some of these issues, rules vary across jurisdictions. In short, as one CCS project developer noted: "If the country wants coal to be a part of the mix, we need to solve the issue of CO_2 transportation infrastructure." Indeed, the DOE concluded in the Quadrennial Energy Review that policy action is required, noting: "Given the upfront capital costs associated with pipeline construction and the absence of policy incentives for reducing industrial carbon pollution, financial support would likely be needed to spur private investments in some regions," and called for "more concerted federal policy."[38]

"The lack of a robust and comprehensive regulatory framework creates an environment of uncertainty that slows down the progress of CCS demonstration projects."

"Challenges to Commercial Scale Carbon Capture and Storage: Regulatory Framework," Monica Lupion, Holly Javedan and Howard Herzog, Massachusetts Institute of Technology, 2015.

However, for many, long-term geologic storage is the crux of the CCS challenge. There are no entities who will take CO_2 and store it. Oil companies will use CO_2 for EOR but are not interested in long-term storage and assuming the responsibilities and steps that go along with that, including monitoring and verification. Schlumberger was the one well-known entity that was trying to start a business in this space, but is now phasing it out. In the words of one expert:

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[35] "Carbon capture and sequestration: removing the legal and regulatory barriers," by M. Granger Morgan and Sean T. McCoy, RFF Press, 2012, pp 56-59. (Morgan and McCoy 2012)
[36] Carbon Dioxide (CO_2) Pipelines for Carbon Sequestration: Emerging Policy Issues, Paul W. Parfomak and Peter Folger, Congressional Research Service, January 17, 2008
[37] Morgan and McCoy 2012, p 60.
[38] QER p 7-24; second quote is from NETL supporting document

"Until there is an entity that will take CO_2 for long-term storage, or unless the federal government steps in and handles all costs of storage and takes on all liabilities, CCS will not move forward."[39]

Specifically, during our earlier fieldwork, we heard a strong message highlighting two major gaps or weaknesses in long-term geologic storage of CO_2:

- Site appraisal/characterization for performance at large scale volumes
- Operating and counterparty risk

There is high confidence that sufficient storage capacity exists and it is generally accepted that with the right geology there are few technical barriers to storing CO_2 underground. In other words, "the geology will work."[40] For example, CO_2 injection at Sleipner in the North Sea has encountered few operational problems in nearly 20 years of experience injecting 1 million tonnes per year owing to a strong regionally extensive seal, very good permeability without pressure build-up, and well-known geology from previous oil and gas exploration. It is not a greenfield site and in many ways Sleipner is an ideal location.

However, where less is known about saline reservoirs, much more site characterization work is required to verify that there is a regionally extensive seal and that permeability is suitable for large volume injection. For example, a coal-fired facility capturing several hundred million tons of CO_2 over the life of the plant, requires storage on order of 100 square miles. Understanding pressure build-up is also important, specifically the impact of large injection volumes of CO_2 on brine displacement, lifetime injectivity, capacity, and other factors.

In short, as one expert noted: "This is a question of learning. Without large scale injections over many years we can't definitively say what will happen with CO_2. Current injection levels of 1 million tonnes per year are insufficient."[41] However, the large up-front cost for site appraisal and characterization – with no guarantee of success –constitutes a barrier to entry for storage. A utility considering a capture project will want to know there is sufficient storage capacity for a number of years, but will not want to pay the cost of appraising a storage site prior to a final investment decision.

Private companies also want some mechanism or policy approach that addresses or shares the risks involved if they invest in a capture project and there is no way to dispose of the CO_2, e.g., a storage site does not get built, the storage site gets shut in, or there is some other commercial or infrastructure related issue that interrupts or precludes the company from providing the CO_2 to an off-taker. In addition, there is the risk that over the life of a storage project, the CO_2 source becomes uneconomic. These risks will become more acute in the event that a carbon price mechanism is implemented.

[39] This comment was received in the course of our research, and was not for attribution.
[40] Reference here: estimates of storage capacity in US from USGS, DOE, IPCC; also add IPCC confidence level here about storage from their 2005 report.

[41] This comment was received in the course of our research, and was not for attribution.

In the U.S., gaps in federal legislation for CO_2 storage, especially with regard to access to pore space and long-term liabilities, need to be addressed to support the commercialization of CCS. For the former, "the injecting party must either own the pore space, have permission from the owner, or have statutory or common law right to use the pore space."[42] There are several categories of long-term liabilities to be addressed: tort (defining responsibility and obligations to pay damages if injected CO_2 causes injuries); climate (requirements to pay compensation if CO_2 leaks into atmosphere); and regulatory (requirements involved in maintaining a CO_2 storage site).[43]

Even where a regulatory process exists, there are concerns over bureaucratic delays. For example, North Dakota applied for primacy overseeing Class VI wells in 2013 but has not yet received approval, and ADM's Class VI permit took three years to obtain.[44]

Finally, while EPA has developed mandatory reporting rules for facilities injecting CO_2 for EOR or long-term sequestration, the rules do not create an accounting system to verify storage, monitor leakage throughout the infrastructure, or establish specific protocols to match the performance of steps in the CCS chain with the specific low carbon policy approach in place.[45]

Europe - Existing Policies and Regulations

Early stage CCS deployment in Europe has been driven solely by climate and low carbon electricity policies rather than by a CO_2 utilization business model, as in the U.S. Furthermore a complex interplay exists between pan-European policies, laws and funding mechanisms developed by the European Commission and approved by the European Parliament, and the national policies of European member states. Consequently, while a suite of broadly supportive CCS policies has existed at European level for some time, including the objective to have up to 12 full scale CCS demonstration projects operating by 2015 (Council of the European Union, 2007[46]), compatible and complementary member state national energy and climate policy on CCS has not materialized to the extent needed to deploy full chain CCS projects.

Even in the United Kingdom, with a comprehensive policy framework including an emissions performance standard, carbon price floor and electricity market reform measures with availability of a contract-for difference feed-in-tariff for CCS power projects (at least in principle if not in practice), CCS projects have not been delivered.

The centerpiece of European climate policy has been the European Union Emissions Trading Scheme (ETS), which was established to create a market in pricing CO_2 emissions that would drive private sector finance and investment in decarbonisation activities and low carbon and renewable technologies, of which CCS is one. A combination of structural problems and the

[42] Morgan and McCoy 2012, p. 91.
[43] Morgan and McCoy 2012, p. 128.
[44] NCC "Fossil Forward," pp 107-108.
[45] Morgan and McCoy 2012, pp 145-146
[46] Council of the European Union, 2007, Presidency Conclusions 8/9 March 2007: http://www.consilium.europa.eu/ueDocs/cms_Data/docs/pressData/en/ec/93135.pdf

economic downturn in Europe has conspired to keep the price on carbon low and insufficient to incentivize CCS projects (and many other technologies as well).

To its credit the EU was an early mover establishing the legal regime for CO_2 storage activities in 2009 and addressing the risks and uncertainties discussed before. Transposition of this Directive into member state laws and regulations across Europe has been a major achievement[47]. While there has been criticism of the comprehensive guidance that accompanied this legal framework and the practicalities of applying some of the requirements of the Directive[48] such as post closure transfer and financial securities to cover long term liability, it has nevertheless provided a rigorous framework in which project developers and national authorities have been able to work.

The critical aspect of CCS policy in Europe has therefore not been one of legal and regulatory gaps, but one of commercial models and financing mechanisms. Both at the pan-European level and national level the CCS policy focus has been on innovation and demonstration. Without a commodity price on CO_2 (for utilization in EOR) and an existing transport and storage infrastructure in place, skepticism of the technical and commercial viability of full chain CCS power projects has led to a paradigm of governments needing to see 'proof of concept'. Within this frame of reference, and having implemented a robust legal regime for storage, the European Commission established two major funding mechanisms: the €1 billion European Energy Program for Recovery (EEPR) and the New Entrant Reserve (NER) 300, which was a monetization program of 300 million ETS allowances competitively allocated to low carbon and renewable power projects including CCS.

Six projects were recipients of the EEPR funding; one in each of the UK, Netherlands, Spain, Poland, Germany and Italy. The latter three have been terminated and the former have undergone substantial change during their lives but no full chain project has been built. The NER300 scheme suffered from the dramatic decline of the carbon price, leaving very little capital available to provide substantive support to full chain CCS projects. The timeframe in which CCS projects under the NER rules needed to be brought to FID was also extremely challenging given the difficult commercial and financing structures required. Finally, the scheme required co-financing from member state governments hosting recipient projects that, in most cases, did not materialize.

A full chain project in the UK CCS commercialization competition[49] did receive an award of €300 million from the NER300 scheme, but this project is no longer proceeding since the cancellation of the UK competition. Poor member state support and follow-up for these pan-European initiatives is a key factor in the failure to have built and commissioned a CCS power project in Europe. As such, the case of Europe demonstrates that merely throwing

[47] Transposition of EU Directives is the process whereby EU member states incorporate the policy and legal obligations enacted by the law-making institutions of the European Union into domestic laws, statutes, regulations and other measures.
[48] European Commission, Support to the review of Directive 2009/31/EC on the geological storage of carbon dioxide (CCS Directive), December 2014
[49] The White Rose Project: http://www.whiteroseccs.co.uk/

financial support at the issue, does not make CCS more viable as a future mitigation technology.

Europe – Gaps and Weaknesses

In Europe, there has been slow progress in addressing transportation and storage infrastructure business models and sustainable low carbon industrial clusters.

Uncertainty over long term aspirations for CCS within the European portfolio of decarbonisation options has created inertia to progressing CCS projects on the one hand, and to establishing a framework in which transport and storage infrastructure can be progressed ahead of market demand on the other. However, increasing recognition of the importance of CCS for decarbonizing energy intensive industries is gradually influencing policy at both EU and member state level.

A concept called the Energy Union[50] has improved the potential for a more stable but flexible policy environment that allows member states the latitude to include non-renewable technology solutions such as CCS in their delivery of emissions reduction targets. Electricity generation is only one part of the low carbon economy and countries will need to develop emissions reduction roadmaps to 2050 that include industrial, heat and transport decarbonisation. Prior to the recent Energy Union policy, which is still being finalized, CCS has been a casualty of ambitious 2020 renewable technology targets, competition with heavily subsidized renewables, and an electricity market focus.

The European Commission has also created the Connecting Europe Facility (CEF)[51] – a €5 billion scheme to facilitate the development of a fully integrated energy market within the EU including the construction of trans-European networked energy infrastructure. Candidates for funding from this facility are known as Projects of Common Interest (PCI) and regional CO_2 pipeline infrastructure is eligible for support.

Although the CEF can support CO_2 pipeline projects in principle the reality is that to actually construct such a regional project requires a guarantee of a characterized storage site at one end and a capture facility at the other. Furthermore, the pipeline would need to have a capacity larger than that of the first project in order to be a viable piece of interconnecting infrastructure. This is exactly the coordination problem previously discussed, and the conditions for accessing finance under the CEF are not conducive to making CO_2 pipeline investments ahead of a market demand. In addition, the CEF does not include shipping as an eligible transport solution. Shipping has been recognized as one possible way of creating optionality of emissions sources to enable investments in large scale storage ahead of demand, whereas pipelines fix the location of source and sink.

With the exception of the one EEPR project in the UK, delivery of large viable offshore storage sites has been left to funding support by national governments and hence none has been characterized to an advanced stage outside the UK's commercialization program and

[50] http://ec.europa.eu/priorities/energy-union-and-climate_en
[51] https://ec.europa.eu/inea/en/connecting-europe-facility

some Norwegian feasibility projects (excluding the commercial Sleipner and Snøhvit gas projects). Relatively small R&D grants for pilot storage projects may be possible from 2017 under the European Commission's innovation funds, Horizon 2020[52] or ERA-NET[53]. But pilot storage projects need a capture facility to deliver CO_2, and hence offshore storage pilots are unlikely under this scheme. Two new innovation funds are proposed for the future based on monetization of ETS allowances: one in the period to 2020 and one ongoing beyond that[54]. For offshore storage site characterization to occur and be taken to the point of investibility, the rules of these funds will need to take account of the special conditions and market failures under which CO_2 transport and storage has to be advanced.

In summary, the European policy approach to CCS at both the pan-European and national levels has been framed in the context of a low carbon electricity generation technology that requires innovation and demonstration to prove it works. Comprehensive policies to facilitate and support the development of transport and storage infrastructure that can be utilized across multiple sectors of the economy, including power generation, industrial processes and low carbon fuels (such as hydrogen) have not been considered. No policies have been developed to address:

- the coordination failure that poses insurmountable investment risk to private sector infrastructure developers;
- regulations for networked and cross-border CO_2 pipeline operations or CO_2 shipping operations;
- decarbonisation of industrial regions utilizing emissions capture clusters with pipeline gathering networks; and
- regional storage hubs to service multiple emissions clusters.

POLICY APPROACHES GOING FORWARD IN BOTH THE US AND EUROPE

There is widespread agreement that risks confronting transportation and long-term geologic storage of CO_2 present a major disincentive for CCS projects. In particular, there is a need to address gaps in the legal and regulatory framework along with the manner in which risk sharing and support mechanisms can facilitate the public and private sectors working together. Many of the specific issues to be addressed have been known for some years, although learning in both the U.S. and Europe continues even with demonstration projects that have been unable to progress to FID and implementation.

United States

There have been a number of serious proposals and other efforts to design effective U.S. legal and policy support approaches. For example, the World Resources Institute published

[52] https://ec.europa.eu/programmes/horizon2020/

[53] http://ec.europa.eu/research/era/era-net_en.html

[54] European Commission, *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments:* *http://eur-lex.europa.eu/resource.html?uri=cellar:33f82bac-2bc2-11e5-9f85-01aa75ed71a1.0024.02/DOC_1&format=PDF*

guidelines for CCS projects in 2008,[55] and the CCSReg Project has developed detailed recommendations for U.S. federal legislation to regulate carbon storage.[56] Many of these were proposed with the assumption that climate policy would spur their implementation, they did not sufficiently address the variety of near-term risks and market failures outlined here, and they typically did not address the relationship between CO_2 and EOR. Nevertheless, these efforts continue to contain valuable core concepts and building blocks for constructing a strong legal and regulatory framework.

For CO_2 pipelines, several options to address current weaknesses include adopting some combination of existing approaches for oil pipelines (which assigns FERC the lead for rates and access, while the states largely oversee siting), or natural gas pipelines (which has an expanded role for FERC including in siting).[57] As noted before, several states are taking the lead in establishing a legal framework for both CO_2 pipelines, as well as storage facilities. As such, the DOE's QER recommended "working with states to promote best practices for siting and regulating CO_2 pipelines."[58] The QER also called for establishing financial incentives for building CO_2 pipelines, specifically citing the tax credits proposed in the administration's FY2016 budget, which could be applied to investment in pipeline infrastructure.

For geologic storage there are a number of alternatives to streamline legal issues related to pore space access, for example to expand EPA's current authority under the UIC program. Regarding long-term stewardship, after a storage site is closed the current operator, a private party, the state, or the federal government could be designated the responsible party.[59] The federal Inter-Agency Task Force on CCS recommended that four options be considered for long-term liability and stewardship: (1) reliance on the existing framework; (2) adoption of substantive or procedural limitations on claims; (3) creation of an industry-financed trust fund to support long-term stewardship activities and compensate parties for various types and forms of losses or damages that occur after site closure; and (4) transfer of liability to the Federal government after site closure (with certain contingencies).[60] Other key issues will be determining division of responsibilities between state and federal authorities, and who pays the cost of long-term site maintenance, monitoring, and reporting.

One representative legislative effort addressing current gaps was the *Carbon Storage Stewardship Trust Fund Act of 2009* (S.1502), requiring that "CCS facilities maintain adequate liability assurance during the active project period."[61] In addition, CCS projects would be required to "pay a risk-based fee for each ton of carbon dioxide injected," with the

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[55] See WRI Guidelines 2008.
[56] http://www.ccsreg.org/model_legislation.html
[57] Morgan and McCoy 2012, p. 60. Morgan and McCoy also describe more detailed variations on siting approaches involving federal "backstop" authority similar to that provided to FERC by the EPACT 2005, or an "opt-in" model where a project could opt for federal backing for pipeline siting.
[58] QER, p. 7-26
[59] Morgan and McCoy 2012, p.127.
[60] "Report of the Interagency Task Force on Carbon Capture and Storage August 2010," U.S. Department of Energy and Environmental Protection Agency, August 2010, p 13.
[61] https://www.congress.gov/bill/111th-congress/senate-bill/1502/text. Liability assurance is defined as privately funded financial mechanisms, including "third-party insurance, self-insurance, performance bonds, trust funds, letters of credit, and surety bonds."

fees allocated to a Carbon Storage Trust Fund established under the Act, used to pay civil claims resulting from CO_2 storage facilities.

The Clean Air Task Force developed a recommendation creating a geologic sequestration utility (GSU), a "specialized, regulated utility that would commercialize injection of carbon dioxide."[62] The GSU would manage CO_2 disposal from stationary sources, such as power plants and manufacturers, and develop geologic sequestration at a system-wide scale. The GSU would charge rates that cover its cost and allow for a rate of return.

Finally, key elements in the design of a comprehensive legal and regulatory framework to support a CO_2 pipeline and storage infrastructure are the design of a GHG accounting framework, as well as a timely and robust public acceptance strategy. The latter in particular will assume greater importance as CCS progresses.

Europe

European CCS policies need to move beyond the innovation/R&D paradigm to one of facilitating deployment if CO_2 transport and storage infrastructure is going to be built in time and at scale to satisfy emission reduction targets beyond 2030. A sufficiently substantive legal regime exists to kick-start deployment of full-chain and part-chain projects, and the next step for both pan-European and national policies needs to be creation of a policy framework that can overcome the key risks and market failures being experienced by the private sector as well as optimizing the deployment scale and pace in a number of important industrial and storage regions within Europe.

European countries with energy intensive industrial regions will need to commence exploring decarbonisation options and pathways as part of their 2050 roadmaps. In the absence of a utilization pull for CO_2 from the upstream oil industry, this exercise presents the opportunity to form regional coalitions with common interest in constructing, operating and utilizing offshore storage sites and transport infrastructure servicing industrial capture clusters and aggregating networks. The policies and funding mechanisms that will support deployment of such infrastructure will take time to create and, given the interaction between European and national governance processes, should commence as soon as possible.

Analysis shows there is unquestionable macro-economic value to the European Economic Area[63] resulting from including CCS in the low carbon technology portfolio. European skepticism of the maturity of CCS technologies (despite a global history spanning many decades) and reluctance to progress essential preparation for transport and storage infrastructure deployment beyond R&D exacerbates the uncertainty for the private sector. Consequently without a long term enduring transition framework that creates certainty for investment in a way that will bring the public and private sectors together, CCS will remain stalled in Europe. This enduring framework should address the risks and uncertainties

[62] Page 50 http://www.catf.us/resources/publications/files/The_Carbon_Capture_and_Storage_Imperative.pdf.
[63] ZEP, *CCS for Industry: Modelling the lowest cost route to decarbonising Europe*, November 2015: http://www.zeroemissionsplatform.eu/

described herein, with attention on emissions clusters (as the *driver*), offshore storage (as the *enabler*) and transportation (as the *connector*).

Emissions Clusters

Policies are required to effectively handle decarbonisation of Europe's energy intensive industries. Focus to date on energy system decarbonisation through renewable subsidies and mandates is only one part of the macro-economic challenge to deliver climate targets. Support mechanisms will be required for trade-exposed industries, and the manner in which costs are socialized throughout the EU will need to be considered in addition to structural improvements to the ETS and effective carbon pricing.

In order to overcome the coordination failure between the various activities in the CCS chain, regional strategic plans will be required that look at low/no regrets scale of infrastructure to handle what would otherwise be residual emissions and hence to define achievable goals for emissions, economic activity and environmental benefits. Known locations of CO_2 pipeline corridors and storage facilities would create positive policy, planning and regulatory conditions for optimizing investment in industrial capture, refurbishment and any new gas-fired power stations needed as part of the electricity mix for security of supply and load balancing. Economies of scale, lowering of risk, and reduction in cost of capital will be achievable for the transport and storage infrastructure through the co-location of power generation and industrial installations.

Offshore Storage

Because of the missing market and coordination failures in Europe the private sector cannot deliver characterization of large scale offshore storage sites from balance sheet funding[64]. Hence new policies that create different commercial model structures pre and post FID are needed for enabling storage development. Example options for the critical pre-FID period include grant funding competitively allocated to private sector site owners or public sector bodies procuring site characterizations for later auctioning[65].

Co-financing support and policies from the European Commission and members states in storage regions are required in order to advance the readiness of storage capacity for investment purposes and prepare for regional storage hubs to service multiple emissions clusters. Some limited potential exists over the coming decade for offshore facilities re-use in the UK, Netherlands and Norway. Operators are, however, reluctant to delay decommissioning simply on the hope that capture projects may materialize in the future, and with the added expense of on-going maintenance costs. Currently governments are not showing any appetite to underwrite the mothballing of facilities. Aggregation of reservoir capacity from multiple sites (depleted fields) with different ownerships adds complications to the re-use model that relevant authorities have not yet begun to address.

[64] The Crown Estate and Deloitte, *A need unsatisfied: Blueprint for enabling investment in CO_2 storage*, February 2016: http://www.thecrownestate.co.uk/media/502093/ei-a-need-unsatisfied-blueprint-for-enabling-investment-in-co2-deloitte.pdf

[65] ibid

A key aspect of an enduring framework for storage will be appropriate risk sharing and coordination between the public and privates sectors. Commercial structures such as public private partnerships and regulated asset base businesses used in delivering other infrastructure for the public good will need to be introduced. Infrastructure capital could be attracted with the right form of CO_2 storage business model; although this would require development of risk sharing mechanisms with government and insurance markets for handling capped liabilities associated with long term storage.

Transportation

Like storage, the coordination failure poses insurmountable investment risk to potential private sector pipeline developers/operators. Although Europe has high level third party access principles no practical experience exists for the specifications, operation and commercial tariff structures that will be required to manage a CO_2 pipeline network. A few countries that have been regulating oil and gas pipelines have the experience to adapt these regimes to CO_2 transport. Policy and regulatory preparation needs to take place to help guide and facilitate the design and deployment of gathering systems in industrial clusters as well as cross-border CO_2 pipeline operations or CO_2 shipping operations.

Conclusion

Although quite dramatic differences exist in the current status of policy, regulation and operations between U.S. and European jurisdictions, there are common market failures and barriers to achieving deployment of CO_2 transport and storage infrastructure at a sufficiently large scale required for the deep decarbonisation of power, industry, heating and transport consistent with the aspirations of the COP21 Paris Agreement. Areas of both Europe and the U.S. are well suited to have CCS as part of a wider mitigation portfolio in the future, although several major hurdles will have to be overcome in order to make that a reality.

The experience to date in Europe has demonstrated that even with a substantial and well-designed regulatory regime, without the appropriate commercial and financial framework supported by policy that can enable a collaborative public and private sector approach, both project and infrastructure delivery will stall. On the other hand, although the extensive existing CO_2 transport and EOR infrastructure in the U.S. can provide a useful springboard for further expansion of the system, new enabling regulations and commercial business models will be required to overcome the same market failures as in Europe. Hence we conclude that the challenges and uncertainties related to carbon transport and storage discussed in this paper can, and will indeed have to, be overcome to avoid them being showstoppers for CCS. Focusing policy exclusively at questions related to capturing carbon and electricity generation is henceforth not recommended.

The key learning from both experiences is that to achieve a transition from the current non-investible status of CO_2 transport and storage to the provision of an essential infrastructure that services multiple sectors of the economy, there will need to be policy innovation that facilitates public and private sector collaboration and financing within a workable set of governing regulations. Because of the massive scale of engineering to deploy this infrastructure, the policy and commercial framework must be designed to deliver a realistic "no regrets" pathway towards emissions targets.

Therefore for CCS to be a viable option as part of a mitigation portfolio we recommend a number of focus areas for policy development and enhancement related specifically to making CO_2 transport and storage infrastructure investible ahead of a level of utilisation that could support future private sector commercial operations.

Recommendation 1: Create a long term 15-20 year stable regulatory and investment environment for delivering a "no regrets" level of CO_2 infrastructure capacity required to avoid residual emissions from back-up power generation, industrial processes, transport fuels and heating in the decade of the 2040s.

Policy focus areas:

1.1 Regulation

Clear and concise harmonised regulations are required in, and between, jurisdictions that enable rather than hinder transport and storage permitting, investment and operations, and which contribute to the establishment of viable market structures and joint market-making functions between the public and private sectors. Regular reviews need to be undertaken within and between jurisdictions to assess efficacy, to ensure compliance is practicable, feasible and cost effective, and to highlight and fix distortions but in a manner that avoids uncertainty so as not to increase political risk and impact or disrupt investment.

1.2 Risk and liability sharing

Policy will need to embrace as a matter of principle sharing of risk and liability between the public and private sectors. The significant barriers to investment in transport and storage created by the lack of a market, the need for planning and coordination between emitters and infrastructure providers ahead of investment, exposure to potential intra-chain performance problems and unlimited storage liabilities, both of which cannot be insured or underwritten in the private sector, will need to be mitigated or removed by Government intervention during a transition to a future fully functioning services market.

1.3 Co-investment business models

New business models that rely on collaboration between Government and industry rather than incentives and penalties in the private sector need to be developed to achieve the right type and level of cost efficient investment in transport and storage infrastructure. This will require structuring projects in some form of public-private partnership (of which there are many variants such as a regulated asset base business model) to deliver investment schemes that share risk appropriately between all parties and enable rather than discourage participation of private sector financial institutions.

1.4 Carbon pricing relativities

Establish national and international mechanisms to enable viability of low carbon or decarbonised industries, transportation and heating solutions that will need to utilise CCS and which are exposed to international competition and different carbon price levels around the world. National or regional carbon pricing or emissions trading schemes are fundamentally flawed if there is no international system of relative pricing for different economies. Trade exposed energy intensive industries will simply move to the lowest cost location. Hence, as a matter of urgency because of the long times taken to develop and reach agreement, multi-lateral arrangements should be negotiated that prevent carbon leakage and create a global level playing field for these types of industries and activities.

Recommendation 2: Establish the public sector institutional capacity to oversee and manage a coordinated approach to market development for CO_2 transport and storage services not reliant on hydrocarbon industry utilisation.

Policy focus areas:

2.1 Storage appraisal

Because of the missing market the private sector cannot deliver characterization and appraisal of large scale storage sites from balance sheet funding. Hence there is an essential role for further government support and funding in both Europe and the U.S. for geologic site characterization that can lead to investible storage sites. Example options for this critical pre-FID period include grant funding competitively allocated to private sector site owners or public sector bodies procuring site characterizations for later auctioning. The recommendation of the U.S. National Coal Council “to certify at least one reservoir” in each of the Regional Carbon Sequestration Partnership regions with the potential to store 100 million tonnes at a cost of $10/tonne is representative of an approach that is required to ensure that suitable, cost effective, long-term geologic storage sites are available to service multiple emissions sources in different geographical regions.

2.2 Inter- and intra- jurisdictional strategic planning

Transport and storage infrastructure development will not stop at regional, state or national boundaries. Suitable CO_2 storage sites may be located outside a jurisdiction’s or region’s borders. Active inter-governmental coalitions will therefore be required to create and manage the strategic and delivery plans for infrastructure that will be consistent with decarbonisation targets. These plans should include funding estimates for progressing storage characterization and appraisal, and transport planning for aggregation networks and pipeline corridors as well as potential inland and seaward shipping routes. Mandated authorities will have to be formed with responsibility for ensuring oversight and progress towards minimum deployment targets.

2.3 Market making institutions

A coordinated approach to market development will be necessary to successfully progress deployment of the no regrets infrastructure capacity at the rapid rate necessary to achieve emissions targets in only a few decades. New market making institutions will be needed to design and implement policies and market transition mechanisms. Various options exist for governments to build this capability. One example is to leverage existing public sector institutions that in combination facilitate delivery and operations through the private sector, which will have limited and underwritten liabilities. Government treasuries, market regulators, subsidy counterparties, and environmental authorities are all examples of existing institutions that can have enhanced mandates to work in a collaborative framework with private sector investors and operators.

2.4 Market transition mechanisms

The inability of the private sector to deliver infrastructure ahead of market demand means that if the minimum level of transport and storage infrastructure required in the 2030s and 2040s (to avoid what we can think of as residual, or unabated, emissions in all of industry, power, heat and transport) is to be achieved there will need to be government involvement in targeted financing schemes and underwriting of risks. Furthermore, low (no) carbon prices and weak future price signals on carbon markets create a dis-incentive for investment, so that government intervention will also be needed to transition the economy to a sufficient level of carbon pricing. A large number of enabling mechanisms exist for government to choose from in a targeted way to address the problems raised in this paper. Examples include pooled funds for storage characterisation and appraisal grants or to underwrite storage and intra-chain performance risks, loan guarantees for infrastructure investment and carbon market contracts to cover long-term leakage liabilities.