

CCS Networks for the UK: Benefits, Impacts and Regulation

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1. Introduction

Most current CCS development work is concentrated on building demonstration plant to provide confidence that the technology can deliver at commercial scales. In the longer term, assuming the demonstration projects are successful, it is likely that a more integrated approach to CCS development using networks (Figure 1) would bring benefits in comparison to multiple isolated facilities. This would repeat patterns of development seen as other energy technologies have emerged, with early isolated systems being replaced by networks. While useful, analogies with the future development of CCS must be treated with care as previous UK network evolution has taken place largely in the public sector, where as it seems likely that any UK CCS networks will be developed privately.

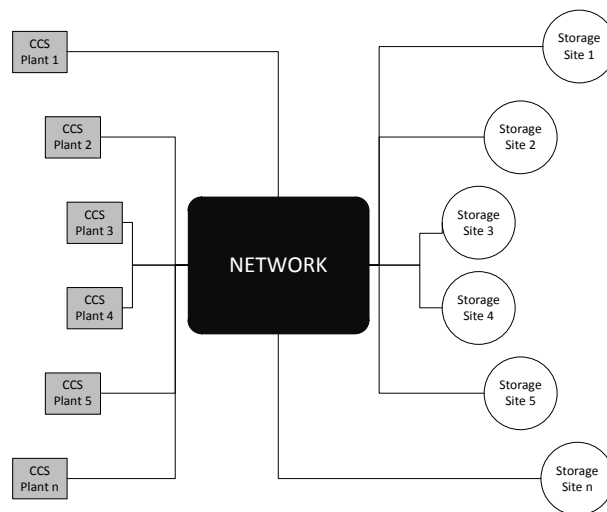


Figure 1: Generic CCS Network

A number of studies have examined the form that CCS networks might take and considered their strength and weaknesses. Table 1 lists a very limited selection of recent studies and summarises their conclusions. Recent UK Government documents appear to recognise that infrastructure sharing and networks could bring wider benefits, but do not indicate a willingness to get involved in directly facilitating their construction. Information for the UK Department for Energy and Climate Change (DECC) Demonstration Projects 2-4 [1] encourages entrants to bring forward any such “...innovative solutions that reduce costs or enhance delivery.” However the documents also state that: “...the cost of oversizing must be supported entirely by the applicant or other private sector investors

without reimbursement by DECC and should not increase the overall risk to the public sector funds invested in the project.”

This summary paper reviews early stage on-going work to investigate the forms that future CCS networks might take, together with estimates of their likely performance with respect to carbon dioxide avoidance. The benefits and dis-benefits that might encourage or discourage stakeholders from co-operating to build networks are also explored. Discussion then turns to the wider risks and environmental implications associated with CCS networks, particularly those not found with isolated systems. Our intention is to bring out the impacts and regulatory issues that are unique to networks rather than CCS in general. We also set out to illustrate that the complex nature of networks means that an integrated whole systems approach is the only means of understanding their impacts.

Study (Region)	Key Conclusions
GCCSI Report: The Global status of CCS: 2010 [2] (Global)	Strengths of networks • Potential to increase carbon dioxide capture over isolated systems • Economic benefits could arise from economies of scale, lower barriers to entry, increased reliability and consolidation of planning issues • Networks would minimise environmental disturbance Weaknesses of networks • Financing initially oversized infrastructure could be problematic • Complex regulatory challenges • Technical interoperability issues between sites • Requirements for CO₂ metering etc.
Element Energy Study [3] (Tees Valley UK)	Strengths of networks • Networks more cost effective than point to point (which are unlikely to be viable at all), and hence will yield greater emissions reductions Weaknesses of networks • Upfront investment in a network (for Tees Valley) is too risky for any single institution to take on • Difficult to attract private financing at commercial rates • A CCS network (for Tees Valley) must follow a challenging critical development path
Neele, Koenen. et al, GHGT-10 [4] (NW and Central Europe)	• Storage capacity is sufficient for NW and Central Europe until 2050, so long as aquifers are used as well as fossil reservoirs
Brunsvold, Jakobsen et al. GHGT-10 [5] (Not specific)	Strengths of networks • Shared infrastructure offers better societal economics than competing/isolated infrastructure, and benefits increase the longer the pipeline network Weaknesses of networks • Government co-funding likely to be necessary for networks • Risks associated with shared infrastructure may discourage stakeholders from investing in it

Table 1: A brief review of some studies on the strengths and weakness of CCS networks in comparison to isolated systems.

2. Carbon dioxide capture potential of networks

2.1 How much carbon dioxide could be captured?

What factors influence the total quantity of carbon dioxide captured by a CCS network? If we make the major assumption of a steady-state system and ignore any dynamic or spatial effects, the key first order constraints will be:

- Total capacity of the storage sites connected
- Carbon dioxide production rate of sources connected, which in turn is primarily a function of the number of sources, and then the fuel, efficiency, carbon dioxide capture effectiveness and utilisation factor of each source
- Transmission capacity
- Equipment operating lifetime

Where the total capture is limited by equipment operating lifetimes, it is possible in principle possible to renew the network and continue capturing more CO₂ until one of the other constraints is reached. However in the light of the on-going decarbonisation of UK of electricity production, and that CCS is a relatively high emission low carbon [6] technology, it seems unlikely that there will be much ‘carbon benefit’ in constructing new CCS plant beyond around say 2050, i.e. in around 40 years’ time. Assuming the lifetime of new power plant and pipelines is 50 years, it hence seems equally unlikely that once a fleet of CCS plant is in existence, there will be value in constructing a second round of replacement fleet once they are life expired. In 50 years’ time CCS plant are likely to represent relatively high carbon technologies, at least so far as base load generation is concerned. For the remainder of the discussion we shall make therefore the rather ambitious assumption that there is only a single iteration of a UK CCS network with a lifetime of 50 years. We will also ignore transmission capacity limitations, and assume that any network is able to move carbon dioxide arbitrarily between sources and storage.

To what extent is the carbon captured by any UK CCS network likely to be capture rate or storage capacity limited? Rather than try to predict the future UK fossil fuel fleet, we have made the further simplification of working with the current fleet, and hence the calculations are illustrative rather than predictive. Table 2 shows the number of years of storage possible for networks connecting combinations of gas and coal fired plant, to the three main categories of geological store: oil and gas reservoirs, trapped aquifers and untrapped aquifers. The smallest lifetime is 65 years, unsurprisingly when all coal and gas plant derived CO₂ is delivered to just oil and gas reservoirs. Given the numerous approximations in the calculation, this comes close to being storage limited, if there is single network iteration with a 50 year lifetime. Aquifer capacities are sufficiently large that, if such locations were used, a network would certainly be capture limited.

Power Station Fuel (GW)	Years of CO ₂ Storage in Storage Type			
	Oil & Gas Reservoir	Aquifers		All UK Storage Sites
		Trapped	Untrapped	
Coal (28GW)	89	102	2854	3045
Gas (22GW)	237	272	7591	8101
Coal+Gas (50 GW)	65	74	2074	2207

Table 2: Years of CO₂ storage in UK offshore reservoirs for current UK power station types (ignoring those <100MW capacity). Annual power station carbon dioxide production for each station is taken from a variety of sources, including operator data and the UK National Atmospheric Emissions Inventory [7]. Storage capacity estimates are taken from an EU supported study by the British Geological Survey [8]. Estimates have assumed that 90% of produced carbon dioxide is captured from each power station.

2.2 Matching production and storage capacity for a network

It is unlikely to be feasible to connect all UK fossil power stations to a network. Although there is some spatial clustering, the full set of larger (>100MW) stations is geographically disperse. Previous work has demonstrated that even with a “backbone” network in place, the marginal costs of connecting ever smaller facilities increases [9], and hence a rule of diminishing returns operates.

The extent of any network needs to be carefully considered therefore. Figure 2 shows the cumulative annual carbon dioxide emissions current from UK fossil fuelled power stations, with the facilities ordered on the horizontal axis in descending rated capacity. Also shown, by the line, is the quantity of carbon dioxide that would be delivered to a network annual if each facility in turn was equipped with a CCS unit capturing 90% of the produced carbon dioxide. As is clear from the figure, more than 50% of the UK’s annual electricity derived CO₂ could currently be collected from a network linking just 8 current power stations, and 60% from a network of 13. Collecting the remaining carbon dioxide, up to the maximum of 90%, would require that a further 39 plant are connected to the network. Clearly there is a diminishing return. To further emphasise this point, the square markers show the additional carbon dioxide that would be delivered to the network by each facility joining the network.

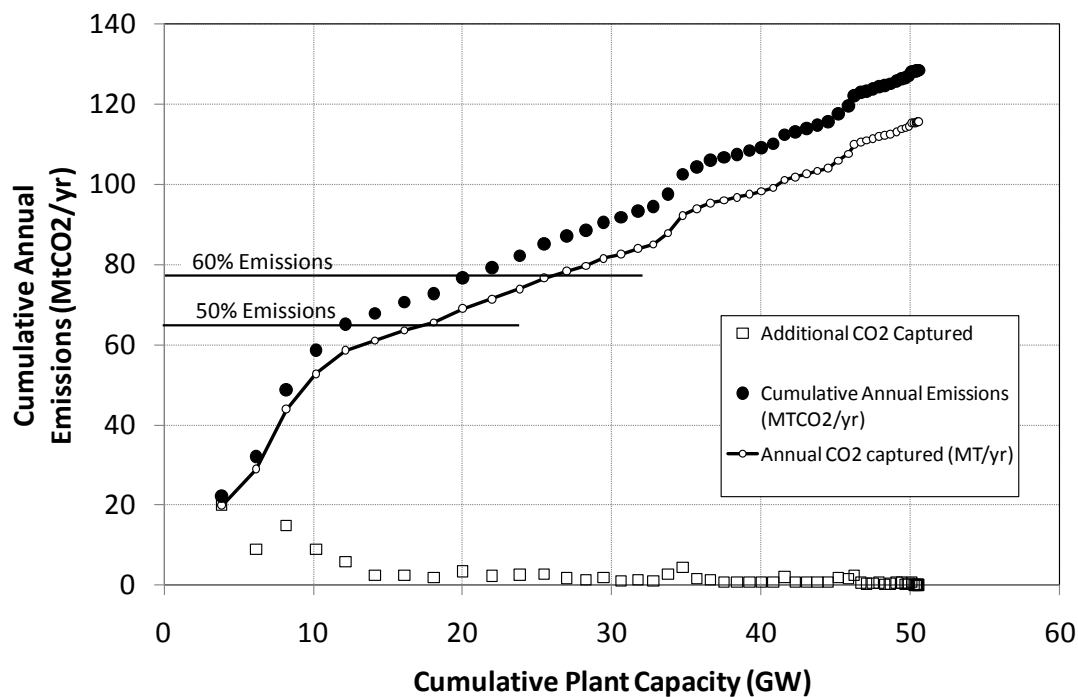


Figure 2: The black circles show the cumulative annual direct carbon dioxide emissions from UK fossil fuelled power plant arranged in order of decreasing rated capacity. Plant with a rated capacity of less than 100MW are omitted from the data. The solid line with markers indicates the total quantity of carbon dioxide that would be fed annual into a network connecting each plant incrementally, when fitted with a 90% capture unit. The points at which 50% and 60% of total annual plant emissions would be captured are marked. The square markers show the annual direct emissions of each plant. All carbon dioxide quantities are in MtCO₂/year.

What are the implications of collecting increasing quantities of carbon dioxide for the storage component of a network? Again using data from the BGS study, the case with 8 power plant would utilise about 36% of estimated fossil reservoir storage capacity over a

50 year lifetime. For a network of the 13 largest plant, about 43% of capacity would be filled. More general results are provided in Figure 3, which shows the proportion of UK Oil and Gas reservoir storage that would be required as a function of the number of power plant connected and the network lifetime. As previously, power plant have been placed in order of rated capacity. The figure indicates a range of network source configurations that would maximise CO₂ capture. For example running a network of the 20 largest plant for 80 years would fill the storage capacity, and avoid the same amount of CO₂, as would running a network of all 52 plant for a little more than 60 years. The relative benefits of differing network construction strategies are currently being evaluated within our on-going work.

Another issue, although not considered in as much detail here, is the diversity of the storage sites. As with sources, there are storage sites of large and small capacity. Planning a network to maximise carbon dioxide storage would of course entail making use of the smaller locations and again diminishing benefits are likely to be encountered as more locations are added. We are currently developing this analysis to better understand relationships between the scope of capture element of a network and the topology of the storage components.

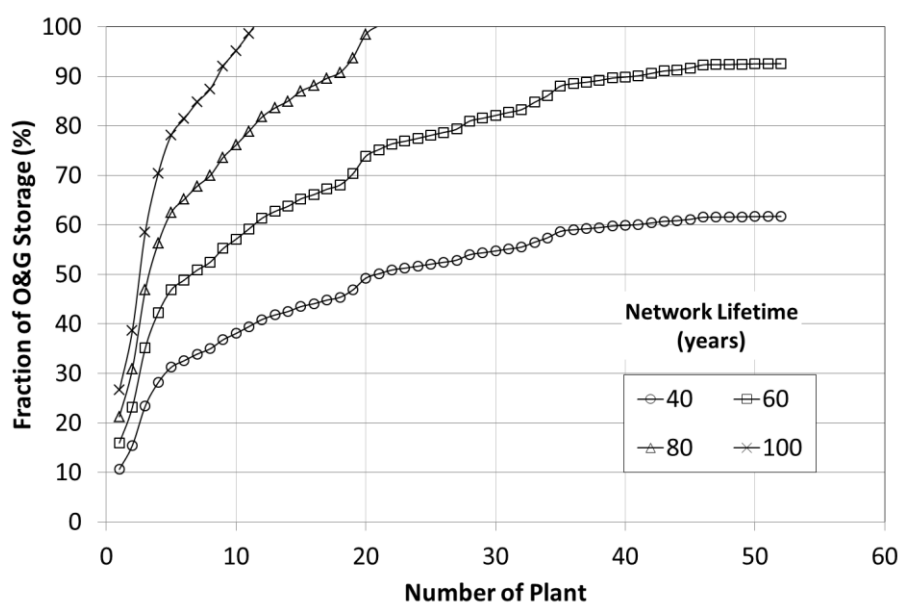


Figure 3: Graph showing the proportion of UK CO₂ storage capacity in oil & gas reservoirs that would be used by CCS networks of differing size, as a function of network operating lifetime. The horizontal axis shows the number of power plant included in the network, and again these have been considered in order of decreasing rated capacity.

3. Benefits and dis-benefits of network development

What might motivate stakeholders to co-operatively develop networks, and what might motivate them to act alone? In this section we qualitatively outline some possible benefits and dis-benefits of CCS network development, in comparison to allowing a set of isolated systems to develop. We consider the whole lifecycle of a network, that is construction, operation and decommissioning. As work is on-going to develop our understanding of the

features of CCS networks, this section is more representative of our starting point rather than our conclusions.

3.1 Benefits of network development

Construction

- Networks could accelerate deployment of CCS and the integration of facilities that might not otherwise implement CCS, and hence yield larger reductions in carbon dioxide emissions
- There is potential for smaller CO₂ producers to be connected to the network than if each producer is responsible storing its own CO₂.
- There are likely to be economies of scale for all those connected, resulting from shared infrastructure, e.g. pipes, land etc.
- Networks will facilitate participation of multiple stakeholders and industries, with the potential to develop business and financing structures that will underpin future commercial CCS markets. Stakeholders will be incentivised to develop new financial structures that address the different investment characteristics of the major elements of the CCS value chain: capture, transport, use and storage

Operation

- Technical issues arising from impure CO₂ streams may be ameliorated. Any excess impurity within a stream coming from a certain capture site will be mixed with other streams. The concentration of the impurity in the CO₂ that reaches the storage site will be reduced significantly therefore.
- Aggregations of sources via a network will make it easier to supply system elements that might benefit from a constant flow rate of carbon dioxide. There have, for example, been suggestions that geological storage sites will require a constant flow.
- Facilitation of cost reductions via the development of regional expertise and production capacity.

Decommissioning

- Arguably it may be easier and cheaper to decommission a CCS network in comparison with several CCS plants because of the shared infrastructure.

3.2 Dis-benefits and difficulties of network development

Construction

- The economies of scale in a CCS network project are premised on over-sizing infrastructure to anticipate later demand. The cost of building a network and making sure it works – one that manages and minimises all the associated risks initially and over time – will be higher compared to a single source CCS scheme. There is considerable financial risk for whoever invests in oversized infrastructure, and it is unclear who would do so.
- Networks are unlikely to arise without some public intervention and/or regulation. Can public budgets be asked to support additional infrastructure based on the future needs of an unproven technology?
- CCS networks are likely to be more tangible to citizens than simple CCS projects, so permitting will be an even more significant issue.

- Getting stakeholders to agree about the development and operation of the network is likely to be very difficult.

Operation

- Handling CO₂ from multiple sources complicates technical considerations regarding specifications for CO₂ quality and systems balancing.
- There is a significant risk that later demand may not materialise, due to uncertainties about how CCS will develop. This would strand investment in oversized infrastructure.
- With carbon dioxide from multiple sources, who is liable in case leakage occurs?

Decommissioning

- There is uncertainty about the level of environmental damage caused by decommissioning a network in comparison to a point to point systems.
- In addition to the future demand for disposal, CCS network projects are premised on future availability of storage. Locating and characterising to sufficient detail the structures most appropriate for high volumes of CO₂ is costlier, riskier and more technically difficult than for smaller, better characterised containers needed to build a simple CCS plant.
- Who is responsible for the closure process? And who is responsible for any long-term liabilities?

4. An industrial ecology approach to networks

One way of considering certain wider CCS network drivers and barriers is through an industrial ecology approach. The concept of industrial ecology is by no means new - it first emerged in the late 1990's as a development within the environmental management field which sought to integrate the notion of sustainability into environmental and economic systems [10]. It has since evolved into an industrial design approach which aims to minimize the environmental impacts of industries by using a systems approach to look at their resource and energy flows [11]. Often, as a solution to minimizing the resource and carbon footprint of industrial entities, it is proposed that industries which may have use of each other's waste materials, ought to integrate geographically and to form so-called "industrial symbioses" thereby mirroring relationships found in the field of ecology [11] [12]. This form of symbiosis is at the heart a form of clustering, though, unlike say, technological clusters such as Silicon Valley which are based around a knowledge/employee centre, an industrial cluster would be based according to the potential energy, water, by-products and wastes exchange possibilities.

The application of industrial ecology concepts to CCS could be considered in two ways. For instance, it might be argued that a network of Carbon Capture plants, that use the same pipeline infrastructure to dispose of the CO₂ waste streams, form an industrial cluster by themselves; seeing as how there is an economy of energy and materials in the build and multiple use of a single infrastructural complex. Furthermore, the combination of waste streams could have the effect of 'purifying' streams from smaller contributors less able to clean their waste streams. This would be done by effectively diluting any impurities in the more CO₂ rich streams of larger industrial players with better capacities for gas filtering.

A CCS network can also lead to a symbiotic relationship (clustering) with other major industrial players such as oil companies for Enhanced Oil recovery [13], chemicals companies or algal biofuel companies [14]. These industries (and others) have uses for carbon dioxide it might make economic sense for other industries to also take advantage of these qualities [15], not to mention bringing sustainability benefits [16]. While one can envision clusters forming around individual CCS plant, a network would require a certain degree of standardization as well as consistency in the volumes and quality of the CO₂ waste streams being exploited. Hence networks would offer more security and reliability with respect to captured CO₂ supply for any external industries that might wish to exploit it, possibly making “industrial ecology” style clusters more likely to emerge.

5. Wider environmental implications of networks

There is little concrete data on the exact effects of CCS activities, in terms of environmental pollution. We do, however, have an idea as to what some more extreme cases might bring, thanks to naturally occurring CO₂ spills such as that in the lake Nyos in Cameroon. We can therefore pinpoint some of the most significant factors in determining environmental risk associated with CCS activities be they on a plant or network scale. From some of the work done by Koornneef et al [17], [18] and Hill [19] we can draw some qualitative conclusions as to what the damages and risks associated with CO₂ escape are and extrapolate the extent to which networks might exacerbate or ameliorate them. We can also draw on experience with small-scale pilot and demonstration projects and EOR facilities.

A qualitative review of some of the more obvious environmental impact risks shows that networks offer an increase in the risk of damage across the board compared to an isolated system. Simply put, the more CCS facilities there are, the greater the risk of an incident occurring. This conclusion is based on the assumption of there being relatively pure CO₂ waste streams in a CCS plant or network of plants, whereby CO₂ is the major pollutant. However, a network of CCS plants could also have risk-reducing tendencies in the form of the unification of standards between industry actors and the enhanced possibility for a dispersal of learning and adopting best practices. In a commercial environment with only a very limited numbers of actors engaged with carbon capture technology, each actor might keep any innovations and experience closely guarded. The development of a network could entail closer collaboration and exchange of knowledge especially if there is strict regulatory control over the quality of the processes. This would incentivise actors across the board to keep good standards and avoid any breach of regulatory requirements [20].

A CCS network could well have the advantage of securing against incidental leaks. As more actors become involved, the more monitoring activities there would be at different points of the pipeline which could lead to enhanced probabilities of spotting any leakages. Furthermore a network could also bring raised standards with respect to pollutants within the captured CO₂. The existence of industry-wide standards for the purity of CO₂ waste streams would inevitably have an improving effect on a capture operator’s emissions filtering and purification processes. This in turn could lead to an overall rise in emission standards. With a network in place, more smaller CO₂ emitters might be able to engage with CCS (and thence meet the network standards) than would be possible without a network [21].

Existing pipeline transportation networks for substances similar to CO₂, such as natural gas, have good risk profiles and few significant catastrophes. Therefore, with adequate regulatory and monitoring measures, there seems to be no reason for CCS networks not to exhibit similar characteristics. Nevertheless, special attention ought to be paid to the geographical placement of carbon capture plants and pipeline routes in terms of proximity to vulnerable ecosystems or densely populated areas. Depending on the criteria for what kind of power generators are allowed to be part of a CCS network, there will be differences in the environmental risk profiles of individual sites. There must be a permitting process evaluating each site and requiring full Environmental Impact Assessments to be completed before any actor is allowed to enter the network. Regulatory requirements for CCS activities, if formulated with a future network in mind, could encourage swifter integration of diverse capture operators as they would not each be facing one-off individual assessments, but would have set guidelines as to comply with.

There is still a great need for further research in to the environmental impacts associated with CCS plants, as well as the wider environmental effects of an integrated CCS network. Inevitably, the wider deployment of CCS that networks are intended to foster will logically lead to a higher probability of a CO₂ leak occurring simply because of the larger volumes involved. Yet there is room for some optimism, as there are also arguments to suggest that a network approach to CCS could have significant benefits in dispersing best practices, standards and knowledge within the industry.

6. Implications for UK regulation & legislation

Considering CCS rollout as part of a network, rather than as an activity for one or two operators has advantages. Networks are conducive to swift dissemination of good industrial practices and knowledge sharing, as well as across the board standardisation of environmental and safety criteria. This could be a strong positive policy driver for the creation of a UK CCS network.

From an industrial ecology standpoint, a network also allows for the emergence of conditions that could facilitate integration of other non-CCS actors who have uses for CO₂. Certainly, unless the CO₂ users produce large volumes of very long lifetime carbon intensive products, it is unlikely that this will make a significant direct contribution to avoiding atmospheric CO₂ emissions. However their inclusion could enhance the economics of a network, and provide a range of local stakeholders with a direct benefit from its creation.

In addition, the act of framing CCS activities as part of a network strategy would also be aligned with a Sectoral Approach to climate change mitigation policy. It would bring together major emitters of CO₂ under a common industrial framework and could thus give more oversight to policymakers on monitoring and regulatory activities. A successful experience with developing CCS in an integrated manner might also have useful regulatory and policy lessons for other low-carbon and renewable industries, especially in its combining issues of emissions reductions and flexible demand and supply in the electricity market.

As things stand, CCS policies are at a nascent stage with international agreements under which such activities may be covered being amended in a piecemeal fashion (OSPAR, London Dumping Convention). Individual governments also differ in their approaches to CCS policies with some adopting a more conservative stance and waiting for more

information to emerge from demonstration and pilot projects; this is particularly true of EU regulators which have adopted a precautionary approach to CCS activities (CCS Directive). However, other states such as Norway, the USA, Canada and Australia have shown an innovative approach to CCS policy, especially in regards to leakage liabilities. For example, in the United States, CCS storage sites have recently been classified under oil and gas storage regulatory frameworks as a new type of well category [22]. Furthermore, even though decisions regarding CCS activities currently lie in the hands of state governments, there has been a move in recent years to originate some form of universal regulatory framework under the Environmental Protection Agency [22]. Networks in particular are considered to be an optimal strategy for CCS development in the US [23]. Even the European Union itself is moving towards a more amenable interpretation of the CCS Directive as evidenced by the positions put forward in the Commission Guidance Documents [24].

There appear to be significant opportunities for UK regulators to consider a flexibly tailored transposition of the CCS Directive to national legislation which takes into account the issue of long-term liability and other significant legislative barriers. If that legislative and policy framework is formulated with a future national CCS network in mind, it could instigate early stage discussions between policymakers and a variety of industry players as to the barriers to CCS rollout as well as some of the advantages from industry wide collaboration. Once that dialogue is initiated it could accelerate dissemination of experience garnered from first off the ground demonstration projects and allow for a swifter uptake of technological and management advances from potential future capture operators thus galvanizing the entire CCS sector. Furthermore, a network approach would take advantage of pre-existing good relationships between policymakers and industry which can lead to invaluable feedback on the appropriateness and ramifications of regulatory and sector financing decisions [25]. Ultimately, this could enhance the precision of monitoring measures, allow for a more inclusive approach to risk management measures and maximise the national return on investment.

7. Conclusion

Carbon capture and storage networks provide an opportunity to maximise the return on investment in CCS technology. Currently there is much uncertainty regarding how extensive a network should be to represent an optimal balance of investment and carbon capture. There is also much uncertainty regarding the wider environmental impacts of networks. We have not attempted to provide answers to these questions, but rather to explore some of the issues. We have also set out to demonstrate the complex, interdisciplinary nature of CCS network analysis, to emphasise the importance of an integrated, whole systems approach to design, regulation and planning.

The quantity of carbon dioxide captures using a CCS network could be ‘supply’ or ‘storage’ constrained. This paper has presented some simple illustrations of the relationships between network extent, effectiveness and lifetime. Rather than try to predict the future UK fossil fuel fleet, we have made the simplification of working with the current fleet, and hence the calculations are illustrative rather than predictive. Where storage takes place only in former oil and gas reservoirs, careful planning will be required to ensure that the network makes effective use of the relatively constrained resource. Where aquifers are also employed, estimated capacities are such that at least 100 years of all current UK fossil

power plant CO₂ emissions could be stored. This is likely to be well beyond the operating lifetime of a ‘first generation’ CCS network, and less careful planning is necessary.

The extent of any network needs to be carefully considered as more than 50% of the UK’s annual electricity derived CO₂ could currently be collected from a network linking just 8 current power stations, and 60% from network of 13. Clearly there will be a diminishing returns effect with respect to carbon dioxide capture as more, smaller plant, are connected to a network. How the CO₂ benefits of an extensive network compare with its wider environmental implications is currently unclear. The potential lifetime of the network and its coupling with the storage capacity and the number of plant connected also need careful consideration.

Networks can offer benefits over point to point systems in terms of the CO₂ captured using CCS. However their wider implications are currently unclear, as there are a number of dis-benefits and complications. It is also unclear how stakeholders could be motivated to construct the oversized infrastructure necessary if an effective network is to be realised. Furthermore, the positive and negative aspects of networks vary between stakeholders, which will hinder the consensus needed to construct them. Yet networks could offer a range of perhaps unexpected benefits in the longer term though clustering effects.

The impact of a CCS network with respect to wider (non-climate) environmental risks is less clear. On the one hand collecting larger quantities of carbon dioxide must increase the risk of an environmental incident. On the other hand, doing so using a network is likely to decrease environmental damage in comparison to a plethora of isolated systems. In addition, there are reasons to anticipate that adopting a network approach to CCS may reduce risk though the regulatory need for common standards any by enhancing sharing of best practice. Regulation will play a key role in fostering the emergence of CCS networks, both with respect to ensuring their carbon dioxide avoidance benefits are realised, and in managing the considerable uncertainties and risks they bring.

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