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A call for standards in the CO_2 value chain

*Randi Neerup[1,‡], Isaac A. Løge[1,‡], Kári Helgason[2], Sandra Ó. Snæbjörnsdóttir[2], Bergur Sigfússon[2], Johan B. Svendsen[3], Nils T. Rosted[4], Peter Blinksbjerg[4], Jannik Kappel[4], Ragni Rørtveit[5], Szczepan Polak[5], Nik Felbab[6], Rasmus Holmer[6], Ajay Arora[7], Jimmy Andersen[8], Bogi B. Jensen[8, 9], Sebastian N. B. Villadsen[1], Georgios M. Kontogeorgis[1], Philip L. Fosbøl[1,]**

[1]Center for Energy Resources Engineering (CERE), Department of Chemical and Biochemical Engineering, Technical University of Denmark (DTU), Søltofts Plads 229, 2800 Kgs. Lyngby, Denmark

[2]Carbfix Iceland ohf., Bæjarhálsi 1, 110 Reykjavík, Iceland

[3]INEOS Oil & Gas Denmark, Teknikerbyen 5, 2830 Virum, Denmark

[4]Amager Ressourcecenter, Vindmøllevej 6, 2300 København S, Denmark

[5]Northern Lights, Byfjordparken 15, 4007 Stavanger, Norway

[6]Horisont Energi AS, Grenseveien 21, 4313 Sandnes, Norway

[7]Dan-Unity CO2 A/S, Smakkedalen 6, 2820 Gentofte, Denmark

[8]Ørsted Bioenergy & Thermal Power A/S, Kraftværksvej 53, 7000 Fredericia, Denmark

[9]University of the Faroe Islands, J. C. Svabos gøta 14, 100 Torshavn, Faroe Islands

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Interoperability is required in a functional CO_2 ecosystem

If the global temperature increase should stay below 1.5 °C, timely action is needed to manage the existing climate crisis. The CO_2 capture and subsequent utilization or subsurface storage, CCUS, is a technology which will help to mitigate climate changes. CCUS can only be achieved through international collaboration, since CO_2 has no borders. This Viewpoint is a wake-up call from North European stakeholders to regulators. The CCUS technology is mature and ready for a global industry, but the regulatory framework is lagging. We urge policymakers to support development of a regulatory framework, which will allow for a holistic CCUS value chain to be implemented. Of special urgency is the standardization of CO_2 impurity levels, which should be a consideration of the cost associated with both conditioning and transport.

In this Viewpoint we highlight critical barriers in the CCUS value chain which include but are not limited to:

- Compatibility problems of the feed streams from different capture processes
- Insufficient transport infrastructure limits the probability of implementing CCUS
- World storage capacity needs to be expanded through reservoir innovation
- Lack of quality and purity standards for downstream CO_2 storage and conversion
- Disconnected industries and cross-national regulations limit the CO_2 value chain

To address these obstacles, we make a run-through of the existing transport and storage business solutions, to list what is being done, where obstacles arise and possible mitigation strategies can be foreseen.

Harmonize the CCUS value chain

Phase behavior of CO_2 is heavily dependent on the gas purity. The CO_2 stream can vary from 75.0-99.9 vol% and contain various chemical species (impurities). These impurities depend on the utilized capture process. For example, solvent degradation products or residual material from the feedstock gas, anything from NOx to hydrogen. These impurities can cause unforeseen condensates, corrosion, hydrate formation, and changes in the phase behavior during transport, injection, and storage of CO_2. Therefore, captured CO_2 must be conditioned and cleaned to be compatible with the transport, utilization, and storage infrastructure. If the CO_2 specifications are not harmonized across the capture, transport, storage and utilization infrastructure, extra conditioning will be needed. It will significantly increase the energy required for handling CO_2. The responsibility for conditioning is unclear and currently no standard on the CO_2 quality exists. We have collected the accepted impurity levels from CO_2 transport and storage stakeholders in Northern Europe (Table 1). Lack of knowledge dictated the levels and high restrictions are the basis for the Table 1. These gas purity levels would decrease the operational cost of transport and storage, but increase the cost of capture and conditioning. Finding a balance between these considerations will be crucial for reducing the cost throughout the CO_2 value chain. Global research and coordination effort are needed, to clarify these impurity considerations. We suggest to implement a flexible regulatory framework, which in the future can accommodate new knowledge on impurities. Without an adaptable framework, efficiency losses could persist in the CO_2 value chain due to sub-optimal CO_2 guidelines. Currently, the optimum operation conditions are unknown, since knowledge and coordination lack for a world scale CO_2 value chain. We suggest to create a harmonizing body under UN or a similar global organization which can create impartial well documented standards.

Table 1. Preliminary CO_2 specification for industrial stakeholders in Northern Europe.

Component	Horisont Energi	Carbfix	INEOS	Northern Lights
CO_2	≥98 mol%	≥95%	-	-
H_2O	≤10 ppm (mol)	<480 kg of water per million standard m^3 in the vapour phase	≤30 ppm	≤30 ppm
H_2	≤600 ppm (mol)	<1%	≤50 ppm	≤50 ppm
N_2	≤0.32 mol%	<4%	-	-
Ar	≤0.5 mol%	<1 ppmv	-	-
CH_4	≤0.91 mol%	-	-	-
CO	≤300 ppm (mol)	<4250 ppmv	≤100 ppm	≤100 ppm
O_2	≤10 ppm (mol)	<10 ppmw	≤10 ppm	≤10 ppm
H_2S	≤9 ppm (mol)	≤20 ppmw	≤9 ppm	≤9 ppm
SOx	≤10 ppm (mol)	<1 ppmw	≤10 ppm	≤10 ppm
NOx	≤10 ppm (mol)	<1 ppmw	≤10 ppm	≤10 ppm
Ammonia	-	<50 ppmw	≤10 ppm	≤10 ppm
Amine	-	<1 ppmw	≤10 ppm	≤10 ppm
Formaldehyde	-	-	≤20 ppm	≤20 ppm
Hg	≤0.03 ppm (mol)	≤0.03 mg/L	≤0.03 ppm	≤0.03 ppm
Arsenic	-	≤0.15 mg/L	-	-
Lead	-	≤0.2 mg/L	-	-
Chromium	-	≤0.5 mg/L	-	-
Copper	-	≤0.5 mg/L	-	-
Nickel	-	≤0.5 mg/L	-	-
Zinc	-	≤0.5 mg/L	-	-
Dioxins, Furans	-	≤1.5 mg/L	-	-
Glycol	-	<40 kg Glycol per m^3	-	-
Sulphur	-	<35 ppmw	-	-
C_2	≤2 mol			

Flexible CO_2 transport infrastructure is needed to get ahead

CO_2 can either be transported by pipelines, trucks, trains, or ships. Pipeline transportation offers the largest operating capacity, while shipping is most flexible. Currently, small amounts of CO_2 are transported across short distances leaving ship transport as the optimal solution; when less than 5 mill. ton of CO_2 per year (Mtpa) is transported to a single storage site (further than 300 km) it is less costly than offshore pipeline transport[1]. Constructing a CO_2 carrier can be done in 1½-2 years, whereas a new pipeline, will require 5-10 years for its planning and construction – time not available in the current climate crisis. Therefore, most stakeholders, are opting for marine shipping. CO_2 shipping has existed for many years but needs to be up-scaled significantly[2]. Shipping companies are currently working on developing CO_2 transport strategies, transporting to onshore facilities in Iceland or Norway or offshore in "virgin reservoirs" or depleted oil and gas reservoirs in the Danish North Sea (Nini West reservoir), the Norwegian continental shelf (NCS), or the Herald reservoir.

However, building the transportation framework imposes large upfront capital investments and without certainty on the future of CCUS from governmental bodies, the economic risk for industries will be too large. The CO_2 transport system is critical infrastructure, and must be in place for any global CO_2 value chain to function. We urge the EU and other global governments to take initiative and create a large-scale CO_2 transport system, to support capture and storage activities, in order to reduce cost.

Upgrade the infrastructure to get additional storage capacity

It is estimated that on a global scale, 5000 Mtpa CO_2 will need to be permanently stored by 2050[3], in order to abate the climate crisis. This is in contrast to the 40 Mtpa CO_2 which are currently stored worldwide[4]. Storing 5000 Mtpa CO_2 is not possible with the available storage capacity and infrastructure in place. It needs to be increased, which can be achieved through upgrading the existing framework. For example, the total storage capacity of the basaltic rock formation in Iceland is estimated to be over 1000 Gt CO_2[5], while the operational capacity at Iceland (Coda terminal) is 0.5 Mtpa by 2026 and is expected to increase to 1.0 Mtpa in 2028 and 3.0 Mtpa in 2031. The bottleneck for storage in the Icelandic storage framework (Carbfix) is the unloading time and quay capacity. The unloading time is expected to take approximately 12-24 hours and the up-time per year is expected to be between 90-95% due to unforeseen weather condition and maintenance. INEOS expects to operate in the Danish North Sea, more specifically in the Nini West reservoir. They will use reservoirs with existing storage capacity of 80 Mt CO_2 and operate with a capacity of 8 Mtpa by 2030. However, by upgrading reservoirs and saline aquifers in the Siri area, with new infrastructure (platforms and pipelines), the operating capacity would be 20-50 Mtpa for 20-30 years, and with a total storage capacity of up to 1 Gt of storage. We advocate for relevant countries to upgrade infrastructures to reach additional storage capacity.

Successful storage and utilizations require standardized CO_2 purities

To reach 5000 Mtpa in 2050, safe and permanent storage is a necessity. This is accomplished by well integrity management during CO_2 injection. Integrity depends on material properties and cementation of the wells plus chemical properties of the injected fluid. If these aspects are not properly addressed, corrosion and leakage can occur over many years of operation. Global and properly documented standards will ensure that wells could be retrofitted to accompany different levels of CO_2 purity, or wells could be repurposed with the option of storing low- or high-grade CO_2 at different reservoirs. This would provide the option for balancing the cost between capture and storage sites. Furthermore, low-grade CO_2 storage might be necessary for cases where capture units produces CO_2 with high impurity levels. Impurities will therefore influence the market value of CO_2, as the cost of operation depends on the source and level of impurities.

CO_2 utilization often requires a CO_2 purity higher than that needed for long term storage. For this reason, it is important that a future CO_2 infrastructure can handle several different qualities of CO_2, for storage, conversion, or food. The CO_2 infrastructure will need to handle this aspect much more in detail, because CO_2 properties can have a significant impact on cost and health. It is unclear what level of impurity can be accepted for utilization but a quality standard has to be in place soon, in order to support the growing market for alternative storage/conversion of CO_2. This information is critical knowledge for example in Ørsted, where CO_2 to methanol conversion is expected before 2030 on the several Mtpa scale.

The European emission trading scheme (ETS) or any similar framework have to accommodate the need for full carbon reduction independent of source where standardized CO_2 purities are considered. We call for additional high purity quality standardization which is targeted certain specific CO_2 utilization applications. A Global coordination is needed to accommodate cross-world infrastructure opportunities. This needs to fit in a trading system similar to ETS and will require low levels of impurities to secure health and safety.

Industry interfaces must be connected: either by regulations or market forces

Transboundary collaboration is a necessity for CO_2 transport, storage, and utilization. Creating both an infrastructure for conditioning, intermediate storage, network for redistribution, and market standards for CO_2 purity would enable a successful implementation for CCUS.

Redistribution of CO_2 by ships across national borders is governed by international legal conventions, mainly the London Protocol[2] and the OSPAR Convention[6]. During 2006 to 2009, the legal barriers to store CO_2 offshore were removed by modifying the London Protocol[2] allowing for cross border CO_2 transportation for sub-seabed storage. However, in order to ratify this amendment from 2009 in the London Protocol the participating countries must grant approvals and therefore, CCUS depends on political action by both international and national governing bodies. The London Protocol does not cover onshore storage. This would drastically bring down the cost of CO_2 storage, which advocates for more onshore-friendly policies to be developed. The EU CCS Directive[7] only applies to storage in areas covered by United Nations Convention on the

Law of the Sea (Unclos) and does therefore not support onshore storage. As time is of the essence, governments must be proactive in regard to storage permitting, building regulations, and updating the EU regulations on CO_2 storage.

International standards for measuring and monitoring the quality of the captured, utilized, injected, and stored CO_2 should be adapted. The standard provides the assurance that accidents related to CO_2 transport and storage are monitored to hinder environmental risks and secure that CO_2 is isolated from the atmosphere. One example could be a multi-purity system based on two main categories. Two qualities divided into high and low graded CO_2: 1. the low-quality CO_2 will be having more impurities like CO, NOx, SOx, H_2, H_2S, and volatile organic components (VOC) whereas 2. the high-quality CO_2 would be of food grade and utilization purpose. This is one suggestion; however, the final solution must be created in between laws, regulation and market forces.

We support to optimize the whole CCUS value chain. There is a need to create well-defined standards for impurities contents for safe handling of CO_2, to control cost of the value chain, to define different quality levels of CO_2 which can feed into different CO_2 value chains, which in the end can create a well-defined market for multiple CO_2 qualities at low cost.

AUTHOR INFORMATION

Corresponding Author

*E-mail: plf@kt.dtu.dk. Tel.: + 45 4525 2868.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. ‡These authors contributed equally.

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ABBREVIATIONS

CCUS, Carbon capture utilization and storage; ETS, European emission trading scheme; NCS, Norwegian continental shelf; Unclos, United Nations Convention on the Law of the Sea.

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Corresponding author biography

Assoc. Prof. Philip Loldrup Fosbøl is responsible for ongoing research in DTU Chemical Engineering on the topic of CCUS (CO_2 capture, transport, conversion and potential storage). He is leading seven larger capture, transport and conversion project aimed at research development from basic science TRL1 to pilot scale application TRL 7. He is leading a research team of more than 20 researchers and currently his group has published numerous publications spanning topics like green fuel (P2X), CO_2 capture, phase equilibria, chemical properties, pilot scale demonstration and results from international collaboration in more than 5 large EU projects.