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Perspective

The underworld of tomorrow? How subsurface carbon dioxide storage leaked out of the public debate

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A R T I C L E I N F O

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A B S T R A C T

This perspective paper illustrates that the critical debate regarding geological storage of carbon dioxide has been discursively marginalised in recent years. However, two crucial factors make it reasonable to assume that significant storage-related uncertainties and challenges still exist.

Firstly, experiences of geological storage are primarily related to enhanced oil recovery. Secondly, recent assessments indicate a doubling of the required quantity compared to what was envisioned back in 2005. Therefore, there seems to be a contradiction: as the visions of geological carbon dioxide storage have grown increasingly ambitious, the risks and challenges associated with storage have been marginalised.

The paper suggests geological storage should become a topic of concern for critical social science and concludes with a reflection on five tentative explanations to the discursive marginalisation: 1) Increasing experience and knowledge have resulted in reduced risks; 2) The climate crisis and urgency have supported a broader acceptance of controversial mitigation options; 3) A shifting focus from fossil fuels with CCS to bioenergy with CCS has introduced new and salient problems that make storage-related challenges seem relatively less significant; 4) Coupling CCS to bioenergy has disarmed critics that primarily argue against prolongation of the fossil fuel era, and finally 5) Familiarisation and normalisation processes.

1. Introduction

The relatively modest development and deployment of carbon capture and storage (CCS) technology in the 21st century stands in contrast to its dramatic discursive shifts. High expectations of CCS among scientists [1,2], industry actors and influential policy-makers in the early 2000s were dashed when funding streams dried up in the wake of the global financial crisis and due to lack of public and governmental support [3–6]. However, the possibility of coupling bioenergy with CCS (BECCS) and generating negative emissions that could help compensate for the historical mitigation failure has renewed the hopes that CCS may be deployed on a large-scale to facilitate the climate transition. With a rapidly diminishing carbon budget, the need to compensate for residual emissions and few plausible decarbonisation alternatives within sectors such as steel and cement, CCS has re-emerged as a key technology in climate policy discourse. Modelling communities have responded to calls for development of 1.5 °C compatible pathways by often including large amounts of negative emissions from BECCS [7,8]. While development and deployment of CCS still lags far behind what is required by most pathways that limit warming to 1.5 °C [9], the widespread sense of climate emergency has shifted the climate policy discourse towards a reluctant acceptance of the need for CCS [10].

In this paper, we argue that one heretofore little noted aspect (but see e.g. [11,12]) of the most recent discursive shift towards reluctant acceptance of CCS is the receding attention paid to critical aspects of geological storage of carbon dioxide. We will briefly illustrate that up until around 2014, geological storage was a contentious issue, but in the current public debate it is treated in a far less polarised manner, with fewer concerns about storage being raised. Here, we provide some tentative explanations as to why this issue has passed into the discursive margin and conclude by suggesting it should again become a topic of public debate and focus area for energy research within the social

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sciences.

Experience of geological storage of carbon dioxide has accumulated during the last 15 years. Hence, the lack of debate on storage capabilities related to CCS in recent years might simply be a result of uncertainty having been reduced to the extent that geological storage is no longer a controversial issue, as is indeed claimed by a few major reports on CCS, especially in USA e.g. [13,14]. However, two crucial factors make it reasonable to assume that significant storage-related uncertainties and challenges still exist.

Firstly, real-world experience of geological storage of carbon dioxide is almost exclusively related to enhanced oil recovery and a few regions [2,12]. This means there is globally still a lack of knowledge and experience of storage in saline aquifers, which, according to the IPCC [15,16], is the geological formation that has by far the largest storage capacity globally.

Secondly, the higher ends of the range in the IPCC assessments of geological storage capacities required over the century for stringent temperature targets indicate a doubling of the quantity compared to what was envisioned back in 2005, when the IPCC special report on CCS was published [15,16]. In a report on geological storage published in 2019, the US National Academies of Sciences, Engineering and Medicine placed such an up-scaling in perspective. Geological storage in the range of 5–10 $GtCO_2$/y globally would require a 100-fold upscale from current levels and would imply the scale of current global oil production [13].

Compounding the issue of increasing demand for geological storage capacity is the fact that carbon dioxide from a range of sources coupled with negative emissions technologies (NETs) needs geological storage in order to reach the levels of GHGs modelled in both 1,5 °C and 2 °C scenarios, leading to pressure to use less proved storage sites [15]. If NETs become commercially viable at scale, as is assumed by many stabilisation pathways, it could in fact make uncertainty about storage greater: “As storage developers move from better to less prospective resources, the time and cost to overcome the uncertainty surrounding injection prospects would probably increase” [12]. Hilaire et al. [11] further observe that while storage capacities in line with 2 °C climate scenarios are scientifically verified, “this is less clear when NET deployment with geological CO_2 storage further increase[s] – like in 1.5 °C scenarios and with the availability of additional NET options with geological storage like DACCS.” With increasing deployment of NETs, there would also be a greater global spatial mismatch between supply of carbon dioxide and the locations of storage facilities [11].

Therefore, there seems to be a contradiction: as the visions of global geological carbon dioxide storage have grown increasingly ambitious, the risks associated with storage have been marginalised in the discourse. The purpose of this perspective paper is twofold. Firstly, we illustrate the discursive marginalisation of carbon dioxide storage by describing a sample of the international public debate on geological storage, which is dominated by experts and researchers, from 2007 until August 2020.[1] Secondly, we provide five tentative explanations for the noted contradictions in the discourse.

2. The international public debate on geological storage of carbon dioxide

During the period 2007 until 2013, the risks of physical leakage of carbon dioxide were an important point of departure for several environmental non-governmental organisations (ENGOs) questioning CCS. The risks and challenges were often cited from the scientific literature in the public debate and ENGO reports and were more frequently reported than in the years following 2013. Friends of the Earth, Greenpeace and other ENGOs repeatedly claimed that both seepage and sudden releases were major risks [17,18]. In Europe, the concerns raised by ENGOs were rebutted by the European Commission, which in 2009 announced its grand vision for CCS in the EU and the so-called “CCS Directive” [19], which established a legal framework for geological storage of CO_2 [19]. In the US, similar critique anchored in the Greenpeace report “False hope – Why Carbon capture and storage won't save the climate” [17] was submitted by 45 American ENGOs in a request to Congress to oppose all CCS projects. Parallels to the Faustian Bargain and nuclear power due to the never-ending commitment to monitor industrial waste, can be traced in the debate at the time (see also [20]), and the Lake Nyos accident in 1986, when carbon dissolved in deep lake waters suddenly erupted and suffocated more than 1700 people and several thousand livestock, also appeared in the debate.[2] The ENGOs' concerns were often in line with and supported by scientists and engineers, and sections from scientific journals that discussed the potential risks were mirrored in mass media. The mentioning of both long-term and short-term risks was frequent, i.e. impact on global warming and water acidity and sudden leakage. On occasion, high storage costs were also cited as a barrier to assuring permanence. In that vein, several researchers maintained that it was preferable to decrease the CO_2 emissions to avoid passing a burden on to future generations. It was sometimes also mentioned that even minor miscalculations could lead to earthquakes as well as annual seepage of more than 1% of the stored CO_2, negating the climate mitigation benefit of CCS. The selection of storage sites and methods to monitor leakage were framed as being of paramount importance for assessing and addressing risks.[3] The discussions in the English-speaking press seem to diverge from the discussions in Japanese press during this period in time. In a study of the mass media debate in Japan (2006–2013), Asayama & Atsushi observe that the risks of leakage were downplayed and they conclude that an optimistic vision paired with high expectations of storage capacity for CCS dominated [21].

Besides the Japanese case, the dominant picture in the international press seems to be one of unacceptably high storage risks. However, a few researchers opposed these depictions in 2008–2011. Geologists Sally Benson, Stuart Haszeldine and Brad Field acknowledged that the leakage risks must be taken seriously, but emphasised that if the storage

[1] The international database Retriever Mediearkivet (Media archive) was used and combinations of the search strings “CCS”, “geological”, “carbon capture and storage”, “leakage”, “seepage” and “acceptance” were applied. The search rendered in ~150 articles published between May 2007 and August 2020. The sample is of course not fully representative of the time period, but can support and illustrate the main arguments. Many arguments are also supported by secondary literature.

[2] Critics Chide EU Carbon Storage Plan, *Business Week Online* (2008-01-29); New Greenpeace report labels carbon capture and storage a “scam”, *Power Engineering* (2008-05-07); Over the coals, *New Scientist* (2008-04-23); Burying our heads in the sand, *The Japan Times* (2008-05-28); Burying CO2: Fix or folly? *Canada.com* (2009-10-08); ‘Carbon storage’ idea leaky, *News24.com* (2010-06-28); DNV signals backing for safe carbon storage, *Business Green*, (2010-12-24); Carbon Capture Projects Imperiled by Worst-Case Scenario: Energy, *BusinessWeek* (2012-02-07).

[3] Iceland Finds New Ways to Trap Carbon, *Inter Press Service* (2008-10-09); Could Ice-like Cages Be Used To Trap Carbon Dioxide Underground?, *Science Daily* (2009-01-15); SA pushes ahead with carbon dioxide storage Atlas project, *Engineering News* (2009-01-16); China pushes CO2 capture, storage questions loom, *Forbes* (2009-11-04); Will carbon dioxide give Miliband the slip?, *The Independent* (2009-11-15); Carbon capture concerns raised, *CBC* (2010-06-28); ‘Carbon storage’ faces leak dilemma – study, *Canada.com* (2010-06-29); Quakes ‘undermine carbon storage strategy’, *ABC Online* (2012-06-19); Environmental hazards or energy solutions? Geophysicists size up energy resources, carbon capture and fracking, *Science Daily* (2013-02-12); Finding the Goldilocks sites to store carbon dioxide underground, *Science Daily* (2013-07-09); Catching carbon, *News24.com* (2013-08-19); A step up for geoengineering, *Nature Geoscience*, (2016-11-30); Doubt cast on Moray Firth carbon storage, *BBC* (2017-11-30).

sites are carefully selected and the technical infrastructure is well designed, the risks are virtually eliminated.[4] Geologists featured repeatedly in the debate, providing assurances that safe storage was attainable, often supported by explicit references to either the commercial full-scale Sleipner facility in Norway, in which approximately 1.0 $MtCO_2$ has been stored each year since 1996, or with reference to natural analogues such as oil and natural gas that has been trapped in reservoirs for billions of years [e.g. [22]]. Nonetheless, the importance of careful site selection and monitoring, and experience through testing and experimenting, was emphasised as well.

Some researchers maintained that the largest obstacle to CCS deployment was public concerns about storage safety, and especially the not-in-my-backyard (NIMBY) effect, no matter how small the risks are according to scientific measurements.[5] In 2011, public opposition was frequently voiced in opposition to concrete CCS projects, for example to CCS plans at the coal power plant Schwarze Pumpe in Spremberg, Germany,[6] and plans to deploy CCS for cement production in Brevik, Norway.[7] In spite of the scientific support for safe storage, Greenpeace maintained that geological storage entailed unacceptably large risks and that the publics' concerns were warranted.[8] The promoters of geological storage on the other hand considered the concerns of the public to be excessive but manageable, as long as suitable and transparent information was communicated. This stance was supported by claims that most geologists and engineers were certain that CCS could be implemented with what they deemed as acceptable storage risks.[9]

In the years following 2014, the attention given to BECCS relative to fossil fuels with CCS increased. In the wake of the Paris Agreement, emission reductions through CCS and negative emissions through BECCS were increasingly depicted as cost-efficient or even necessary methods in climate stabilisation scenarios. In subsequent IPCC reports, fossil fuel with CCS and, even more so, BECCS featured heavily in mitigation pathways compatible with reaching ambitious climate targets [23].

2.1. The geological storage risks becomes more marginal, 2014–2020

The relative increase in attention paid to BECCS coincided with a marked decline in publicly voiced concerns over the safety of geological storage. In contrast with previous years, remarkably few references to potential problems with geological storage are published in mass media after 2014.[10] In 2015, several geoscientists and engineers edited an open letter to Christiana Figueres, the then Executive Secretary of the UN Framework Convention on Climate Change (UNFCCC). The scientists announced evidence demonstrating the safety and climate efficiency of geological CO_2 storage, and that leakage harmful to either ecosystems or humans was highly unlikely. In the unlikely event of leakage, methods were claimed to be available to detect the CO_2 before it reached the surface.[11] Several statements by other scientists, in support of the call to Figueres, were reported in mass media in subsequent years. These statements were often underpinned by scientific reports and experience from storage projects, e.g. Sleipner and Snøhvit.[12]

The minor interest directed towards geological storage was not just confined to the public debate and can be illustrated by the fact that only 3 out of 215 critical review comments pertaining to BECCS, submitted to the second order draft of the IPCC SR1.5 published in 2018, dealt with geological storage issues. Storage concerns in the SR1.5 review comments were instead almost exclusively related to carbon storage in soils and biomass [8]. The German government was one of the few exceptions; it raised concerns over the lack of discussions on the evidence for safe long-term geological storage of CO_2. As pointed out by Hansson et al. [8], the IPCC reviewers massively questioned the realism of large-scale deployment of BECCS on a gigaton scale on grounds of competition for land, insufficient potential for biomass supply, and large risks of biodiversity loss. Among the few actors that also raised concerns over the safety of geological storage, the other type of critique just mentioned was still in the forefront.

From 2014 until 2016, it was primarily spokespersons for large ENGOs (Greenpeace, Biofuelwatch, Heinrich Böll Foundation, ETC Group, and the Climate Action Network) who underscored that geological storage was highly problematic and a key reason for avoiding BECCS. It was argued that geological storage was expensive, risky and unproven, and thus not suitable for mitigating climate change. The critique was further pronounced by underscoring that captured CO_2 was often used for enhanced oil recovery (EOR) rather than permanent storage. The large ENGOs expressed a distrust in the capabilities of managing these operations safely. They also emphasised the counter-productive incentives it creates for the fossil fuel industry to entrench fossil fuel infrastructure and gain more revenues.[13] Over time it seems like the arguments evolved and the focus was instead directed towards the other and seemingly overshadowing environmental risks and drawbacks of BECCS, rather than towards questions concerning geological storage. Thus, for some time the public debate reflected the more critical responses in the review process of SR1.5. After 2016, Linda Schneider at the Heinrich Böll Foundation was the only person who in our review maintained, in 2019, the argument that geological storage risks were main concerns, although she did so explicitly in relation to fossil fuels with CCS, without mentioning BECCS.[14]

Nonetheless, a number of researchers and engineers involved in developing or investigating BECCS, who took a generally supportive

[4] Burying our heads in the sand, *The Japan Times* (2008-05-28); SA pushes ahead with carbon dioxide storage Atlas project, *Engineering News* (2009-01-16); Coal at centre of fierce new climate battle, *The Guardian* (2009-02-15); Burying CO2: Fix or folly?, *Canada.com* (2009-10-08); Method puts carbon-capture and storage 'leaks' to test, *The Engineer* (2011-12-13).

[5] Reducing emissions is the primary way to fight climate change, study finds, *Click Green* (2014-06-02); Residents weigh global benefits, local risks in views of climate change measures, *Science Daily* (2013-11-01); Residents Weigh Global Benefits And Local Risks In Views Of Climate Change Measures, *Individual.com* (2013-10-31).

[6] Greenpeace Blasts Berlin for Secrecy on Carbon Storage, *Spiegel Online* (2011-02-16).

[7] Can cement clean up its act?, *Eco-Business* (2016-06-17).

[8] Greenpeace Blasts Berlin for Secrecy on Carbon Storage, *Spiegel Online* (2011-02-16).

[9] Government told: use social media to allay public's nuclear fears, *EAEM* (2012-07-09); Intelligence Squared: Keeping Technology Options Open For a Low Carbon Future. *Huffington Post UK* (2012-10-18); Australian government pledges AUS$25 million in funding for CCS project, *worldcement.com* (2015-02-03).

[10] There was a sharp increase of articles covering CCS and/or BECCS in 2011 and the coverage has been relatively stable on a high level until 2022. Thus, the more marginal position of geological storage risk cannot be explained by general decline of interest in CCS/BECCS.

[11] Burying our heads in the sand, *The Japan Times* (2008-05-28); Coal at centre of fierce new climate battle, *The Observer* (2009-02-15); Greenhouse gas storage possible - NZ study, *ONE News* (2011-12-13); Method puts carbon-capture and storage 'leaks' to test, *The Engineer* (2011-12-13); World-first experiment on carbon-capture completes first stage, *Fish Update* (2012-06-29); Geoscientists and engineers stress CCS is safe, secure and effective, *World Coal* (2015-10-09).

[12] StatoilHydro says subsea carbon store does not leak, *Reuters UK* (2009-03-05); Subsea Ravine Leaks Present a New Headache for Carbon Capture in North Sea, *Scientific American* (2012-09-18); Delivery to the deep: storing CO2 beneath the seabed, *Offshore Technology* (2014-03-06); World can 'safely' store billions of tonnes of CO2 underground, *Eco-Business* (2018-06-13).

[13] IPCC proposes sucking carbon out of air as climate fix, The Guardian (2014-04-07); Could we suck up climate change?, *Daily Mail* (2014-04-11); The myth of net-zero emissions, *Eco-Business* (2014-12-24); Radical realism about climate change, Eco-Business (2016-11-03); Climate conference's smoke and mirrors, The Japan Times, (2015-07-13); Eine langsame gratwanderung, *Die Tageszeitung* (2016-05-26).

[14] Kapitale: Klimakempner, Junge Welt (2019-03-31).

stance, emphasised the challenges of geological storage. The concerns raised by these actors were more frequently voiced in 2014 and the following years.[15] Risks of leakage were mentioned, but the risk of climate change was seen to override the risk of leakage and the latter is not presented as a dealbreaker for BECCS.[16] A few researchers stressed that geological storage was a relatively new concept and the long-term risks were consequently difficult to oversee.[17] One example is given by a set of Earth system modellers, Ella Adlen and Cameron Hepburn at University of Oxford, who are engaged in developing BECCS and who, in November 2019, stated that "there are several problems and challenges to overcome before such a large utilization could be achieved".[18] In line with the group of Earth system modellers, Wilfried Rickels at the Kiel Institute for the World Economy and colleagues stated that geological storage capacity was not fully regarded when modelling the global potential of BECCS. Consequently, they regarded the fact that the issue of long-term storage was unresolved as the largest challenge for BECCS.[19] These and similar concerns raised by researchers and engineers developing BECCS were seldom picked up by ENGOs and other actors critical of BECCS in the period 2014–2020. We have only found a few examples: Jennifer Morgan from the Netherlands declared that the great uncertainties concerning the technical feasibility, safety, sustainability and cost of long-term storage were reasons for rejecting the results of the SR1.5, and she labels BECCS as a "false solution".[20]

To summarise the observations, we argue that the critique directed towards geological storage voiced by ENGOs critical of CCS and BECCS faded after 2014, replaced instead with voicing critique of other seemingly more salient and critical aspects of BECCS. The critical aspects of geological storage were occasionally raised by researchers and engineers after 2014, but framed as manageable problems. The marginal discursive position of geological storage issues is still reflected in the current mass media debate, i.e. at the beginning of the 2020s. In commentaries and articles addressing BECCS, it is commonly assumed that CO_2 can be safely stored, although some exceptions to this general message are notable.

3. Five tentative explanations for the marginalisation of geological storage risks

This study is rooted in the observation that, despite recent calls for CCS and BECCS and the unprecedented demand for geological storage of CO_2, the previously voiced concerns and challenges regarding geological storage of CO_2 have become more marginal in the international public debate. The observation is supported by our review of international mass media articles published from 2007 to 2020 and can also be supported by secondary literature. In a comprehensive mapping of debates by Waller et al. [24] including web-querying and document analysis about what was excluded from CCS assessments, with a focus on recent technoscientific controversies in the UK about BECCS and afforestation, geological storage concerns were not even identified or brought up by the authors, despite them highlighting concerns revolving around land and even less salient issues (e.g. supply chain and overseas emissions). The observation can also be supported by Lane et al.'s [12] claim that the general understanding of geological storage capacity and availably is permeated by over-expectations and that two persistent misconceptions dominate the current understanding of CCS: (1) that geological factors are not likely to limit the global expansion of CCS; and (2) that all regions will probably have access to sufficient geological storage capacity. We will return to Lane's [12] analysis in the concluding discussion and relate it to our tentative explanations presented in the following.

We propose five tentative and partly overlapping explanations for the recent shift in the public debate on geological CO_2 storage: 1) Increasing experience and knowledge has actually resulted in improved geological storage methodologies with reduced risks; 2) The increasing urgency of the climate crisis has supported a broader acceptance of controversial mitigation options; 3) A shifting focus from fossil fuels with CCS to BECCS has introduced new and more salient problems that make storage-related challenges seem relatively less significant; 4) Coupling CCS to bioenergy has disarmed critics that primarily argue against prolongation of the fossil fuel era, capitalism or carbon lock-in; 5) Familiarisation and normalisation processes have eased the controversiality of storage technology.

The **first** explanation is also the most obvious: risks and challenges associated with geological storage may in fact have decreased with increasing experience. Major challenges may have become sufficiently managed, or at least the belief that they can be managed has become more widespread. Experience with CO_2 injection for EOR now spans more than 50 years and encompasses 125 $MtCO_2$. Experience with injections for dedicated storage purposes has also increased significantly, operating for more than 25 years with an accumulated storage of more than 45 $MtCO_2$. The experience gained has provided insights on risks, well integrity, and cost [13,14], and can be labelled as an impressive progress in developing and demonstrating technologies for tracking plume migration, detecting leakage, and understanding pressure build-up and rock-water-CO_2 reactions. Nonetheless, several significant knowledge gaps related to scaling up are acknowledged, including geology (e.g. site characterisation), regulations (e.g. permit difficulties), and risks (e.g. induced seismicity) [13], but overall practising geological storage has increasingly become a manageable matter of learning-by-doing that, if paired with proper communication strategies and suitable regulations, is manageable.

The **second** explanation emphasises the increasing urgency of the climate crisis, which entails a broader acceptance of mitigation options including controversial technologies. Since the adoption of the Paris Agreement in 2015, acceptance of methods to achieve larger volumes of negative emissions has also risen [e.g. [25]]. Broecks et al. [3] show that citizens tend to be less negative towards CCS when they accept climate change as a major risk. The more widespread sense of climate emergency and a rapidly diminishing carbon budget for holding global heating below 2 °C have arguably increased acceptance of environmental risks associated with climate change mitigation, including risks related to geological CO_2 storage. It is a matter of risk trade-offs in which the environmental risks of geological storage seem less significant than passing climate thresholds in temperature overshoot scenarios, relying on other relatively untested mitigation methods, or opting for even more controversial methods like solar radiation management.

Instead of focusing on the absolute risks, the **third** explanation embodies the notion that in a new context of adding "bio" to CCS, the challenges related to geological storage have relatively speaking diminished. Many of the concerns around BECCS raised in, for example, the IPCC SR1.5 revolved primarily around land-use conflicts, lack of supply of biomass and goal conflicts for achieving SDGs [8,16]. Several scientific papers and also news media articles focus on the lack of realism in supplying the biomass needed for BECCS on a gigaton scale, at least without seriously compromising the fulfilment of other SDG targets (e.g. biodiversity, food security, land conservation, competition for water resources) and low carbon efficiency of the supplied biomass, and also the lack of realism in the science underpinning the gigaton visions [8,10]. Thus, despite the problems of geological storage potentially remaining, they have become relatively smaller in relation to the new

[15] How we could save the world from global warming before our time is up, *Gizmondo UK* (2014-04-17).

[16] Hoovering up CO2 with CCS-equipped biomass powerplants, *Spectrum online* (2015-02-18); Pathways for a Brazilian biobased economy: towards optimal utilization of biomass. *Biofuel, bioproducts and biorefining* (2019-02-20).

[17] Industry continues to make progress on carbon capture, *SPE* (2019-11-04).

[18] Ten ways to use CO2 and how they compare, *Carbon Brief* (2019-11-07).

[19] Carbon removal requires multiple technologies, *Physicsworld.com* (2019-11-13).

[20] Why forests are the best technology to stop climate change, *Al Jazeera* (2018-11-06).

and more salient challenges to which "bio" brought attention.

The **fourth** explanation also concerns the discursive reframing that has followed from the emergence of negative emissions as a key idea in the climate policy realm, especially through the stronger coupling of CCS to bioenergy since around 2015 [10]. It seems plausible, given the different framings and connotations, that arguments against CCS that relate to risks of fossil fuel entrenchment have been disarmed to some extent by an increasing focus on using BECCS to phase out fossil fuels or CCS in the cement or steel industries. In a recent study in the UK and the Netherlands the idea of CCS at industrial processes attracted a higher degree of public acceptance than CCS at coal fired plants, however previous research does not provide a coherent picture and it seems like the context has great influence on the degree of acceptance, e.g. if the activity is seen as a means to increase or maintain economic growth in the region [38].[21] Likewise, the idea of balancing emissions from hard-to-abate sectors such as steel and cement and emissions in developing countries through negative emissions technologies (NETs) has won the support of actors that see the continued growth of such sectors in emerging economies as important from a climate justice perspective. We should therefore consider the politico-discursive power of the concept of NETs, and its ability to mobilise "discourse coalitions" encompassing diverse actor groups, each of them eager to be seen to pursue aggressive climate policies for different political reasons [see also [10,24]]. The discursive reframing may also disarm the critique sometimes used against CCS, such as prolongation and deepening of fossil fuel use and sustaining a capitalistic status quo [see also [2]]. Breaking with such a coalition in support of NETs, by questioning geological storage capabilities for example, would then come with significant political risk.

The **fifth** explanation forwards that critique of geological storage has declined with increasing familiarisation and a gradual public acceptance or absence of protests because of fewer geological storage projects and more offshore storage. These processes are bundled together because they are results of normalisations. Acceptance studies, focusing on risk and benefit perceptions across regions with different levels of CCS deployment, have shown that attitudes tend to shift towards acceptance as people become more familiar with the CCS technology and by living near projects [37]. Bioenergy has also been shown to have more positive connotations than fossil fuels among lay people [26] and research further indicates that leakage of stored CO_2 of biogenic origin is viewed as less damaging to the climate than leakage of CO_2 of fossil origin [27]. The increase in acceptance, or the absence of protest, is arguably also mirrored in mass media. Public acceptance is generally stronger for offshore geological storage [28], which in recent years has emerged as the preferred option in the industry. On-shore storage has become prohibited in some parts of the world and a general shift in focus towards offshore storage has meant that storage-related risks to human health have lost prominence.[22] Risks of physical leakage are thus discussed as a climate rather than an immediate health issue, which is a more acceptable form of risk among the public [22]. Storage-related risks have therefore become less newsworthy. The normalisation process can also be seen in mass media. Our brief analysis of the mass media debate gave a few illustrations of initial references to spectacular events like the Lake Nyos incident and risks associated with geological storage. Such expressions seem to have become scarcer over time. In the public debate on CCS in the Netherlands, for example, geological storage was the most frequently mentioned component of CCS in the years following mid-2009, three times more common than mentions of carbon capture [29]. Possibly the CCS debate has matured and is less prone to reinforce risks, and instead mass media are now more prone to mirror the first of our tentative explanations, namely assumptions that the geological storage risks have decreased.

4. Concluding words

The achievement of stringent climate stabilisation targets is increasingly depicted as relying on the realisation of grand-scale CCS and BECCS, which in turn is ultimately conditioned by abundant, accessible, and safe geological storage capacity. If the first tentative explanation holds most explanatory value, one can argue there are no major reasons to be concerned over the marginalisation of critical aspects of geological storage in the debates. That explanation implies a consensus in the scientific and engineering discourses that risks and uncertainties have become more manageable over time. However, that explanation can be countered by Kelemen et al.'s [22] call to acknowledge the enormous difference between megaton scale and gigaton scale, and that one should not assume past experience of geological storage is a guarantee of massive deployment in the future. Lane et al. [12] show that estimates of available storage space are vastly overestimated (in China and India) or are extremely challenging to fulfil (in the USA) and, besides the physical restrictions, it can take decades to develop institutional settings that support meaningful storage rates (see also [2]).

We might be inclined to believe, then, that uncertainty related to storage of CO_2, besides site-specific experiences, has not been reduced in any absolute sense, but rather marginalised in the CCS discourse due to other risks being given greater priority. Our explanations 2–5 set out some, in our view, plausible reasons for this discursive shift. If this hypothesis is correct, the issue of available and safe geological storage capacity would be likely to re-emerge in a situation where much political and economic capital has already been sunk into the deployment of CCS infrastructure, and when significant amounts of emission space have already been claimed on the assumption of uncertain storage space being available.

In a recent paper, Mohan et al. [31] discuss the risks opened up by the ambiguity around the concept of negative emissions. If the abstract numbers derived from global assessments are not made concrete, they argue, the critically important discussions on the politico-economic effects of different NET deployment scenarios risk being postponed. The understanding of CO_2 storage capacities can be seen in this context, as another example of a general tendency within climate policymaking towards depoliticisation (see also [32]). As long as the CO_2 storage capacity is treated as virtually unlimited (see also [31,33]), climate policy discourse will allow for ambiguity that carries significant political, economic and, not least, climate-related risks. We would like to conclude, therefore, with a call for politicisation of the issue of geological storage in the CCS discourse. It is a call we direct in particular to the social sciences, who we argue have the responsibility to influence such politicisation.

In a paper on the debate on hydraulic fracking and CCS in France, Chailleux [2] highlights a tendency towards scale-related myopia in the social sciences dealing with the subsurface. Because studies tend to focus one-sidedly on either the local or the global context, and only on the extractive industries and countries harbouring such industries, Chailleux argues the politics of the subsurface have remained insufficiently discussed [2]. To his analysis, we would add a temporal aspect that tends to depoliticise the issue of CO_2 storage. There seems to be a lack of proactive politicisation, which may be explained by the absence of real-world storage projects, in particular onshore projects where the political potential is highest. As long as the grand idea of geological storage remains on the plane of the purely ideational, it could therefore be left untouched by critique.

Now, global climate policy is not lacking in seemingly intractable political conflicts, and one might easily sympathise with those who wish to keep momentum in the development of national net zero strategies and want to abstain from opening yet another box of potential

[21] Broecks et al. (2021) provides guidance to studies that have reviewed the public awareness of CCS in different national settings.

[22] According to Buttnar el al., [30] 40% of the CO_2 storage would rely on onshore reservoirs in 2100, and that only a China, South East Asia and Central South America could supply most of the geological storage required for a 2 °C scenario.

controversy. As argued by Lane et al. [12], however, “a poorly conceived CCS strategy, based on unrealistic storage expectations, could both increase the need for negative emissions and diminish the chances that they could be delivered.”

To avoid the issue of CO_2 storage becoming yet another climate policy being kicked down the road, we would therefore call for the critical social sciences, especially in the field of energy research, to bring it back from its current position in the margins of the discourse [see also [35]]. As long as storage-related conflicts are explored by the social sciences mainly through acceptance studies or highly localised perspectives [e.g. [34,36–38]] the larger issue of premising net-zero strategies on storage capacity being virtually unrestricted will remain depoliticised, to the detriment of all future mitigation. As Anshelm and Galis have shown in a study of nuclear waste management in Sweden, critical social science and also ENGOs may contribute crucially to speeding up the development of socially and environmentally sustainable strategies for coping with environmental problems, both by identifying the need for further studies and increasing the chance of problem identification [39]. As such, controversy and politicisation are not to be avoided, but rather welcomed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] A. Hansson, M. Bryngelsson, Expert opinions on carbon dioxide capture and storage—a framing of uncertainties and possibilities, Energy Policy 37 (6) (2009) 2273–2282.
[2] S. Chailleux, Making the subsurface political: how enhanced oil recovery techniques reshaped the energy transition, Eviron. Plann. C. Polit. Space 38 (4) (2019) 733–750.
[3] K. Broecks, C. Jack, E. ter Mors, C. Boomsma, S. Shackley, How do people perceive carbon capture and storage for industrial processes? Examining factors underlying public opinion in the Netherlands and the United Kingdom, Energy Res. Soc. Sci. 81 (2021), 102236.
[4] K. Pietzner, A. Schwarz, E. Duetschke, D. Schumann, Media coverage of four carbon capture and storage (CCS) projects in Germany: analysis of 1,115 regional newspaper articles, Energy Procedia 63 (2014) 7141–7148.
[5] M. Fridahl, M. Lehtveer, Bioenergy with carbon capture and storage (BECCS): global potential, investment preferences, and deployment barriers, Energy Res. Soc. Sci. 42 (2018) 155–165.
[6] A. Lefvert, et al., What are the potential paths for carbon capture and storage in Sweden? A multi-level assessment of historical and current developments, Energy Res. Soc. Sci. 87 (2022), 102452.
[7] S. Beck, M. Mahony, The IPCC and the new map of science and politics, WIREs Clim. Change 9 (6) (2018), e547.
[8] A. Hansson, J. Anshelm, M. Fridahl, S. Haikola, Boundary work and interpretations in the IPCC review process of the role of bioenergy with carbon capture and storage (BECCS) in limiting global warming to 1.5°C, Front. Clim. 3 (34) (2021).
[9] EASAC, Forest Bioenergy, Carbon Capture and Storage, and Carbon Dioxide Removal: An Update, The European Academies’ Science Advisory Council, Halle, 2019.
[10] S. Haikola, A. Hansson, J. Anshelm, From polarization to reluctant acceptance–bioenergy with carbon capture and storage (BECCS) and the post-normalization of the climate debate, J. Integr. Environ. Sci. 16 (1) (2019) 45–69.
[11] J. Hilaire, J.C. Minx, M.W. Callaghan, J. Edmonds, G. Luderer, G.F. Nemet, J. Rogelj, M. del Mar Zamora, Negative emissions and international climate goals—learning from and about mitigation scenarios, Clim. Chang. 157 (2) (2019) 189–219.
[12] J. Lane, C. Greig, A. Garnett, Uncertain storage prospects create a conundrum for carbon capture and storage ambitions, Nat. Clim. Chang. 11 (11) (2021) 925–936.
[13] NAP, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, National Academies of Sciences, Engineering, and Medicine and The National Academies Press, Washington, DC, 2019.
[14] Safe Geologic Storage of Captured Carbon Dioxide – DOE's Carbon Storage R&D Program: Two Decades in Review, National Energy Technology Laboratory, Pittsburgh, April 13, 2020.
[15] IPCC, in: Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos, Leo Meyer (Eds.), Special Report on Carbon Dioxide Capture and Storage, Cambridge University Press, Cambridge and New York, 2005.
[16] IPCC, Global Warming of 1.5 °C: An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, Intergovernmental Panel on Climate Change, Cambridge, 2018.
[17] Greenpeace, False Hope: Why Carbon Capture and Storage Won't Save the Climate, Greenpeace International, Amsterdam, 2008.
[18] J. Anderson, J. Chiavari, Understanding and improving NGO position on CCS, Energy Procedia 1 (2009) 4811–4817.
[19] Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009.
[20] D. Spreng, G. Marland, A.M. Weinberg, CO2 capture and storage: another Faustian bargain? Energy Policy 35 (2) (2007) 850–854.
[21] S. Asayama, A. Ishii, Selling stories of techno-optimism? The role of narratives on discursive construction of carbon capture and storage in Japanese media, Energy Res. Soc. Sci. 31 (2017) 50–59.
[22] P. Kelemen, S.M. Benson, H. Pilorgé, P. Psarras, J. Wilcox, An overview of the status and challenges of CO2 storage in minerals and geological formations, Front. Clim. 1 (9) (2019).
[23] S. Haikola, et al., Limits to climate action: narratives of bioenergy with carbon capture and storage, Polit. Geogr. 88 (2021), 102416.
[24] L. Waller, T. Rayner, J. Chilvers, Searching for a public in controversies over carbon dioxide removal: an issue mappings study on BECCS and afforestation, Sci. Technol. Hum. Values (2021), https://doi.org/10.1177/01622439211043568.
[25] F. Schenuit, R. Colvin, M. Fridahl, B. McMullin, A. Reisinger, D.L. Sanchez, S. M. Smith, A. Torvanger, A. Wreford, O. Geden, Carbon dioxide removal policy in the making: assessing developments in 9 OECD cases, Front. Clim. 3 (7) (2021).
[26] L. Wallquist, S.L.O. Seigo, V.H.M. Visschers, M. Siegrist, Public acceptance of CCS system elements: a conjoint measurement, Int. J. Greenhouse Gas Control 6 (1) (2012) 77–83.
[27] A. Vinca, J. Emmerling, M. Tavoni, Bearing the cost of stored carbon leakage, Front. Energy Res. 6 (40) (2018).
[28] L. Mabon, S. Shackley, N. Bower-Bir, Perceptions of sub-seabed carbon dioxide storage in Scotland and implications for policy: a qualitative study, Mar. Policy 45 (2014) 9–15.
[29] M. de Best-Waldhober, D. Daamen, A. Faaij, Informed and uninformed public opinions on CO2 capture and storage technologies in the Netherlands, Int. J. Greenhouse Gas Control 3 (3) (2012) 322–332.
[30] I. Buttnar, et al., The role of bioenergy for global deep decarbonization: CO2 removal or low-carbon energy? GCB Bioenergy 12 (3) (2020) 198–212.
[31] A. Mohan, et al., UNFCCC must confront the political economy of net-negative emissions, One Earth 4 (10) (2021) 1348–1351.
[32] A. Malm, White Skin, Black Fuel – On the Danger of Fossil Fascism, Verso, 2021.
[33] J. Palmer, W. Carton, Carbon removal as carbon Revival? Bioenergy, negative emissions, and the politics of alternative energy futures, Front. Clim. 3 (2021), 678031.
[34] S. L'Orange Seigo, S. Dohle, M. Siegrist, Public perception of carbon capture and storage (CCS): a review, Renew. Sust. Energ. Rev. 38 (2014) 848–863.
[35] A.M. Gormally, N.O. Markusson, M. Bentham, The pore space scramble: challenges and opportunities for subsurface governance, Geoforum 95 (2018) 70–77.
[36] P. Tcvetkov, A. Cherepovitsyn, S. Fedoseev, Public perception of carbon capture and storage: a state-of-the-art overview, Heliyon 5 (12) (2019), e02845.
[37] E. Dütschke, K. Wohlfarth, S. Höller, P. Viebahn, D. Schumann, K. Pietzner, Differences in the public perception of CCS in Germany depending on CO2 source, transport option and storage location, Int. J. Greenhouse Gas Control 53 (2016) 149–159.
[38] K. Broecks, et al., How do people perceive carbon capture and storage for industrial processes? Examining factors underlying public opinion in the Netherlands and the United Kingdom, Energy Res. Soc. Sci. 81 (2021), 102236.
[39] J. Anshelm, V. Galis, The politics of high-level nuclear waste management in Sweden: confined research versus research in the wild, Environ. Policy Gov. 19 (4) (2009) 269–280.