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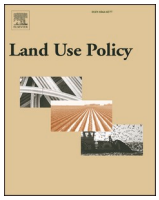

Underground futures: The essential role of the subsurface in a net zero carbon future

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ABSTRACT

This viewpoint examines the overlooked yet crucial role of the underground in achieving net zero carbon transitions. Drawing on insights from the Underground Futures scoping study, a collaboration between Lancaster University and the British Geological Survey, the viewpoint explores how subsurface spaces, once associated with extraction, are now central to energy storage, carbon sequestration, and geothermal heat generation, and the governance and regulatory challenges this presents. Through interviews and focus groups with UK stakeholders, it identifies governance, limited data, and a lack of integrated planning as major barriers to sustainable underground use. The viewpoint bridges geoscience, spatial planning, and concepts from political geology to ultimately suggest that the underground is a dynamic and active component of planetary change, that is both shaping and being shaped by human efforts toward a sustainable net zero future.

1. Introduction

Whilst discussions about net zero carbon transitions inevitably focus on activities at the surface, such as the increased implementation of renewable energy technologies and energy storage (DESNZ, 2020), a key component of the transition is often overlooked. That is the essential and shifting role of the underground in enabling such a transition to take place. Once associated with extractive practices and fossil fuel production, the underground now holds a pivotal role in our (geo) social futures (Clark and Szerszynski, 2020). For instance, those spaces that have been created underground from the extractions of resources (including depleted oil and gas fields, coal mines, salt caverns) are now new sites of commodification in their ability to 'store' both temporally and permanently materials needed for, or produced from, the net zero carbon transition (Gormally et al., 2018).

This viewpoint is based on outputs from a scoping study called 'Underground Futures' that was a collaborative project between Lancaster University, UK and the British Geological Survey (BGS). The aim of the project was to explore the role of the underground/subsurface in a net zero carbon future with a range of stakeholders. These included members of the department for Business Energy and Industrial Strategy (BEIS),[1] Environment Agency, Radioactive Waste Authority and The Crown Estate. Stakeholders were chosen due to their role in utilising underground space or its governance. In total, one focus group (5 participants) plus 3 expert interviews were carried out. These discussions took place in late 2019/ early 2020 and have since been supplemented with informal conversations with The Mining Remediation Authority,[2] colleagues at the British Geological Survey (BGS) and the Environment Agency (EA).

This viewpoint bridges research on subsurface planning and regulation from a resource perspective, with conceptualisations of thinking about the subsurface in the 3rd (volume) and 4th (time) dimensions (Elden, 2013, Bridge, 2013, Gormally, 2018, Childs, 2020). We take this further by using outcomes from our own preliminary research data to formulate our view on how we should be thinking about *underground futures*. This viewpoint focuses on the UK but has lessons that could be replicated globally. As such, we proposed to highlight an agenda of research to take forward that will ensure a sustainable and 'just' approach to the underground and its (re)use under a net zero framing. We argue that the decisions we make today with regards how the underground is used will have significant impacts on the success of our net zero transition. It will also have significant implications for future

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[1] This is now the Department for Energy Security and Net Zero (DESNZ)
[2] Formally The Coal Authority

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generations in terms of determining the overall long-term 'health' of the underground and what it is able, or is no longer able to provide for us. We outline an overview of the challenges ahead (Section 2.0), the need for more effective planning and governance (section 3.0), and consider the underground as part of a changing planet (Section 4.0).

1.1. The role of the underground in the net zero transition: Challenges ahead

A net zero carbon future currently pictures a place for renewable technologies that will require energy storage such as hydrogen, heat and compressed-air (CAES), underground energy sources such as geothermal heat, carbon capture and storage (CCS) and nuclear energy, all of which will require either permanent or temporary use of the underground (Evans et al., 2009). However, there are both temporal and spatial dimensions to both the storage/disposal need and the geology itself. These temporalities range from days (as we currently have with short-term energy storage of natural gas in salt caverns), long-term storage (weeks, months), to a permanent repository, as is the case for geological storage of CO_2 from CCS and the disposal of high-level radioactive waste (Evans, et al., 2009). Many of these also use the same or similar types of subsurface properties eg. Salt caverns or pore spaces can be used for different types of gas storage, yet there is little coordination or knowledge sharing of these activities and their coordinated role in a net zero carbon future (Gormally et al., 2018). Moreover, the geology dictates access to energy, the ability to store, bury or dispose, and this does not always align with our societal needs (GO Science, 2024; The Royal Society, 2023). For instance, hydrogen or air storage repositories and geothermal heat from mine water would ideally be near urbanised areas, or radioactive disposal under a community that is willing to accept it.

When referring to underground futures, we refer to the myriad of ways the underground might be used as part of the net zero transition. Important international work has focused on global challenges associated with land use, land tenure and climate change, such as the United Nations Conventions to combat desertification (UNCCD, 2022) and work by Chigbu (2023) on connecting and tenure to land restoration. However, we would suggest here that, although important, this work still conceptualises the problem at the surface level, rather than within the underground itself.

We specifically focus on the underground in the UK, however many of the challenges related to this will be transferable to other regions, whilst acknowledging the different place-based conditions both above and below the surface. This includes different geological settings, history of extraction and political and socio-economic conditions of the region. The UK is geologically diverse, and this has led to a well-documented history of extraction such as coal-mining, North sea oil and gas extraction, quarrying of construction and industrial materials such as aggregates, clay, silica, gypsum, potash, salt, and metals such as Tungsten and Gold (DESNZ, 2019). In addition to extractive practices, the UK has also used and proposed to use different scales of underground spaces for the short-, medium- and long-term storage of energy related materials. This includes salt caverns for the short-term storage of natural gas and medium-term storage of hydrogen and/or compressed air energy storage, depleted oil and gas fields and long-term deep storage repositories for high-level radioactive waste. The timescales referred to vary in order of magnitude from a number of hours (natural gas storage) to months (hydrogen and compressed air) to millennia and beyond (carbon and radioactive waste). The UK is replete with legacy infrastructure and disused coal mines are now being explored for heat storage and generation of geothermal heat from old mine water (eg. See The Mining Remediation Authority[3] and UKGEOS Glasgow[4]).

The importance of the underground in the net zero transition is beginning to gain some traction with recent reports such as the UK's GO Science (2024) Foresight report on the Future of the Subsurface (2024). This report covers a wide range of issues including data access, competition and congestion, and regulation. There is additionally a body of academic literature that details the challenges of planning with regard to the underground, and its current and future use in the UK. This includes the challenges of regulation, terminology and coordinated planning (Grecksch, 2021; Volchko et al., 2020). More broadly Gardiner et al., (2023) present a comprehensive overview of the specific role of the Geosciences in the energy transition and, as others have emphasised, the need to engage a wide range of stakeholders when we try to consider the *value* of the underground.

Whilst this existing work is important when discussing the challenges ahead with regard to the underground and its current and future use, what we argue here is that we collectively need to push our thinking even further forward. We need to consider the role of the underground specifically in the framing of net zero and more broadly make decisions that are aligned with 'Just' energy transitions (Wang and Lo., 2021). What is proposed here is that we need to think more deeply about our wider 'geo-social' relations over time; the reciprocal way in which the earth has shaped society, and society has shaped the earth (Clark et al., 2020). Put more simply, we need to think about how our actions today will shape our future ongoing relationship with the underground and how the decisions we make today will lead to areas of (un)possibility, going into the near and far future.

2. Need for more effective planning, mapping and governance

Our history with the subsurface therefore offers a range of new underground futures. These need to be considered carefully as some require the use of the same or similar spaces (eg. pore space/salt caverns), which are needed on very different timescales, and may need to be accessed through adjacent subsurface areas of existing underground use. For instance, pore space used for the storage of CO2 from CCS in adjacent 'parcels' of the subsurface to oil and gas extraction (Gormally et al., 2018). Therefore, a range of different stakeholders will need to be involved and coordinated in their approach to thinking through how the underground might be used in a net zero future that complements one another and doesn't hinder future use.

3. Challenges of planning and regulation

Grecksch (2021) notes that the underground is currently heavily regulated but the approach to this regulation is fragmented. This was echoed by our stakeholders who commented on the 'siloed' nature of subsurface knowledge, data and regulation. Grecksch (2021) goes on to comment on the 'out of sight, out of mind' nature of the subsurface and the need for greater 'underground dialogue' around property rights and regulation.

The use of the underground is changing. Once a space heavily relied on for extraction (coal, oil and gas, water), it is now being conceived as a place for both retrieval of resources and storage and/or burial of gases or materials needed in the net zero transition. This change in use was acknowledged and discussed with our participants. However, there was recognition that there is currently little discussion of these issues in national or local policy, or co-ordination across different stakeholders. There was some discussion of targets aimed at reducing carbon or meeting net zero, such as city level strategies (e.g., Manchester 2030)

[3] Mine water heat: The Mining Remediation Authority (accessed 03/06/2025)

[4] Glasgow observatory overview | UK Geoenergy Observatories (Accessed 03/06/2025)

and changing government priorities in relation to net zero. However, participants reflected that much of this work is siloed with stakeholders becoming experts in their particular field and less discussion of how that field will intersect with another as new technologies, new uses and new extractions happen as part of the UK's net zero ambitions:

"….*this comes back to the mapping exercise, we don't know the potential of the underground resource is because we don't know what's there and what we can do… So we don't understand the resource I suppose is what I'm struggling to say.*"

A range of stakeholders we spoke with discussed the huge potential the subsurface offers and how that might be utilised in the transition to net zero. However, there was a lack of knowledge (this knowledge was mainly discussed as data or subsurface assets) and co-ordination in the approach amongst relevant stakeholders. A need for better 'mapping' of underground resources was called for but the challenges of this were acknowledged as was the idea of 'conflicts' of underground space:

"Mapping is the other thing at the back of my brain because, there's lots going on and we're already coming across people having ideas for schemes, where they all want to use the same bit of land but they don't know about each other."

"We've spatially mapped the terrestrial environment quite well but actually, we don't map the subsurface in the same way."

Often when land or 'surface use' is visualised it is conceived as a 2-dimensional space e.g. location of energy infrastructure such as cabling, power stations, and pylons. We are not the first to discuss how the underground forces us to re-conceptualise our energy infrastructure, and the subsurface more specifically, as a 3-dimensional space (Bridge, 2013). However, we do propose here that thinking in 3D needs to encapsulate the net zero transition more specifically, and to move beyond conceptual thinking into more active policy and planning engagement.

4. The challenges of data and co-ordination

The terrestrial environment has provided us with an abundance of environmental data that has been collected for decades through technological advancements and now feed into work on 'Big Data' (Bakker and Ritts., 2018). Data accrued on the subsurface is much harder to come by. There are a number of reasons for this (1) it's hard to access and varies on its physicality and geological properties (2) data that does exist is largely commercially sensitive, (eg. owned by oil and gas companies, the mining remediation authority and other commercial enterprises) and (3) to date there has been an 'ad-hoc' approach to how the subsurface has been used. For instance, the industrial revolution led to mass extraction of resources in industrial nations particularly of fossil fuels such as coal, oil and gas. One of our stakeholders noted: *"[There's] huge existing potential within the existing legacy infrastructure we have – we just don't understand it yet"*.

One such approach to help reveal this potential is to develop 'Smart Earth' technologies that enable visualisation of the subsurface in ways that, to date, have not been possible and examples are beginning to emerge on the use of Artificial Intelligence (AI) to better characterise subsurface properties (eg. Sun et al., 2022; Gutiérrez-Oribio et al., 2025).

4.1. The underground as part of a changing planet

Much of the emerging interest in the subsurface frame it as a 'system' to be managed, utilised and regulated. Whilst we agree with the usefulness of using this framing for decision making and policy-making, we would like to emphasise that future thinking of the subsurface should go beyond this and consider that the underground has a form of *agency* in and of itself.

By this we mean that the underground is not a static environment for us to merely engage with, extract from, store within, and plan its utilisation. The underground *moves*. It reacts to both how we engage with it and to its wider environmental conditions. For instance, the underground has an abundance of fractures, fissures, pore spaces, caverns, tunnels and forms of infrastructure (pipework, cabling, utilities, transport systems etc). These are not set in 'stone', they change both as a consequence of what we do with it, and in response to surrounding environmental and geophysical conditions. A good example of this is the London Underground tube network. The network is located in London Clay and is slowly heating up as the clay has absorbed heat from passengers, tube trains and its mechanical operations over time.[5]

Recent focus has included the subsurface in climate adaptation thinking, for example how the underground might be used as part of climate adaptation strategies, but with little reference to how climate may change the underground in the future.

5. Conclusion - Underground futures

The underground is a dynamic and key component of the net zero transition that requires a profound shift in how we plan, regulate, and conceptualise our relationship with the subsurface. Historically viewed as a space of extraction, the underground is now emerging as a site of storage, and innovation and will be central in meeting our long-term energy and climate goals. However, this shift presents complex challenges relating to competing uses, governance, and gaps in subsurface knowledge and data. A coordinated, multi-scalar approach that integrates geoscientific understanding with social, political, and ethical dimensions is therefore essential. Moreover, the underground must be understood not merely as a system to be managed but as a living, responsive environment that both shapes and is shaped by human activity and planetary change. Decisions made today regarding underground use will have long-term impacts on environmental stability and intergenerational equity. As such, future research and policy must work towards an integrated framework for sustainable use of the underground. One that acknowledges the complexities of the subsurface and ensures equitable access to its resources.

CRediT authorship contribution statement

Hazel Napier: Writing – review & editing, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gormally-Sutton Alexandra:** Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to write and abstract for this work. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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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[5] Tunnel vision: the challenge of cooling the London Underground - CIBSE Journal accessed 07/06/2025

Data availability

The data that has been used is confidential.

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