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Storage potentials for carbon-rich products in Germany - a database and outlook on final storage of products derived from negative emission technologies

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Abstract. Addressing the need to achieve the EU's net-zero emissions target by 2050, the inclusion of unconventional measures for CO_2 removal from the atmosphere into the technology portfolio appears necessary, meaning the implementation of carbon dioxide removal (CDR) or negative emissions technologies (NET). Various CDR approaches are explored for their potential in carbon dioxide removal but do not take into account the final disposal of by-products and end products as well as the potential of different areas for the required long-term storage. To complement existing methods, the NETPEC project (Negative Emission Technologies based on Photo-Electro-Chemical methods) proposes a novel approach utilizing (photo-)electrochemical methods to convert CO_2 into solid or fluid products for secure long-term storage. The aim of this work is to identify potentials for the final disposal of such carbon-rich products resulting from negative emission technologies and to develop a database of sites and areas in Germany, taking into account a broad regional distribution and sufficient storage capacities. Promising sites for storage are identified, highlighting the importance of comprehensive data collection and systematic evaluation. A database is established to catalog past, present and potential mining activity in Germany, providing essential information on storage potentials, regulatory considerations and potential estimations. Despite challenges in data availability and regulatory complexity, re-purposing old mining sites and mining related areas for storage offers significant potential in mitigating climate change by securely sequestering carbon-rich products. This study builds on the collection of data via the geological state offices towards the creation of a database on the determination of areas and estimations of potentials. The assessments suggest that even if only 1% of these mining-related areas are considered suitable for storing carbon-rich products, a significant surface area of around 990 km^2 - larger than Berlin - would be available. Additionally, another 348 km^2 of subsurface space - surpassing the size of Frankfurt (Main) - could potentially be utilized. These figures highlight the immense storage potential of Germany's mining sites, making them key to the project's long-term carbon storage strategy. By utilizing existing infrastructure and geological formations, the project addresses the urgent demand for large-scale carbon storage while minimizing environmental impact and reducing costs. This database serves as a crucial foundation for informing, decision-making and ensuring effective implementation of carbon storage initiatives and shows possibilities for the subsequent use of such areas.

1 Introduction

Anthropogenic climate change is primarily driven by carbon dioxide (CO_2) emissions from human activities like burning fossil fuels, land-use changes, and industrial processes (Smith et al., 2024). The long-lasting impact of CO_2 causes global temperatures to rise and remain elevated for millennia. Thus, in order to meet the Paris Agreement goal of keeping global temperature rise well below 2°C, with efforts towards 1.5°C, significant and rapid reductions in emissions urgently required. Achieving net-zero CO_2 emissions is crucial, which involves both reducing emissions and removing existing CO_2 from the atmosphere. The urgency to meet the EU's net-zero emissions target by 2050, as emphasized by the IPCC (2018), also demands unconventional measures for CO_2 removal. The IPCC's pathways to the 1.5°C target assume the need for net negative emissions in the latter half of the century, necessitating the implementation of carbon dioxide removal (CDR) technologies (McLaren, 2012; IPCC, 2018; Fuss et al., 2018, 2020, 2021; Smith et al., 2024).

For a technique to qualify as CDR, it must involve the capture of CO_2 from the atmosphere and the permanent storage of the captured CO_2 (Smith et al., 2023). Short-term storage can still contribute to climate goals, but carbon released within a year is not considered as CDR (Smith et al., 2024). The necessity of removal and sequestration of carbon dioxide also entails the responsibility of managing the resulting byproducts from such technologies. This includes pure carbon dioxide, which is actively removed out of the atmosphere and stored in underground repositories, but also different products derived from various CO_2 sequestration methods (Smith et al., 2016 a; Bui et al., 2018; Fuss et al., 2018; IPCC, 2018; Fuss et al., 2021; Smith et al., 2024). Numerous products and byproducts contribute to CO_2 sequestration from the atmosphere (biochar, wood, peat, rock powder) and are suitable for long-term disposal or storage (Tab. 1). One of the most common methods is presented by direct air carbon caption and storage and CCS (DACCS;CCS IPCC, 2018, 2023). It refers to a collection of technologies and techniques aimed at capturing carbon dioxide emissions, either from the atmosphere (DACCS) or from large industrial sources such as power plants. The captured CO_2 is then stored or sequestered to prevent it from (re-)entering the atmosphere (CCS; Li et al., 2018; Bui et al., 2018; Smith et al., 2024). The storage in geological formations is, despite several uncertainties that will be described later on, one of the most promising technologies for climate change mitigation as it has been attributed the potential of having a key role in negative emissions strategies (Bui et al., 2018; Smith et al., 2024).

Another carbon dioxide removal approach is afforestation and reforestation. It aims for the carbon dioxide reduction with plants and trees trough natural photosynthesis to extract the CO_2 and fix the carbon within the biomass (McLaren, 2012). The production of biochar and its use for soil enhancement and plant fertilization is a rather new method for subsequently achieving negative emissions. Biochar is a carbon-rich material derived trough pyrolysis from organic substances like wood or agricultural waste that has the potential to improve soil quality (Smith, 2016 b). Consequently, biochar production presents an means of extracting CO_2 from the atmosphere, but it is not a permanent removal (Thengane and Bandyopadhyay, 2020; Smith, 2016 b), as long as it remains in the carbon cycle. With regard to the storage of NET-products in exploited mines, Thengane and Bandyopadhyay (2020) quite appropriately describes their idea of biochar and its final storage of the carbon from CO_2 as "biochar mines". Already here the point of the long-term storage of carbon-rich products is pointed out figuratively.

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Table 1. Overview on common and new CDR methods and their educts/products.

CDR Method	Abbreviation	Educt/Product	Aggregate state
(Direct Air) Carbon Capture and Storage	CCS, DACCS	Carbon Dioxide	gaseous[a]
Biochar	-	Wood → Biochar	solid[b]
Enhanced Weathering	EW	Rock Powder+CO_2 → Rock Powder	solid/powdery[c]
Ocean Alkalinity Enhancement	OAE	Rock Powder+CO_2 →Rock Powder	solid/powdery[d]
Reforestation/Afforestation	AR	CO_2 → Wood	solid[e]
Peatland and Wetland restoration	-	CO_2 → Peat	solid[f]
Photoelectrochemical approach	PEC	CO_2 → Graphite; Oxalate; Oxalic Acid	solid or liquid[g]

[a]Bui et al. (2018); Vilarrasa and Rutqvist (2017), [b]Smith (2016 b) [c]Zondervan et al. (2023), [d]IPCC (2023), [e]McLaren (2012), [f]McLaren (2012), [g]May and Rehfeld (2019)

Enhanced weathering (EW) is a process of accelerating the natural process of rock weathering, which chemically binds carbon dioxide of the atmosphere (Strefler et al., 2018). This approach involves finely grinding (ultra-)mafic rocks, such as basalt, and spreading them over large land areas where agricultural processes are still realizable (IPCC, 2023). Spreading those grinded rocks in the oceans is another approach called ocean alkalinity enhancement (OEA). New studies reveal that silicate mineral weathering in fact could also release a non-trivial mass of carbon dioxide back into the atmosphere (Zondervan et al., 2023).

There are further existing approaches like wet- and peatland re-wetting or the protection and recovery of mangrove biotopes trying to mitigate climate change by removal of carbon dioxide (Table 1; McLaren, 2012; IPCC, 2023). Furthermore approaches of geo-engineering like solar radiation management, e.g. stratospheric aerosol injection (SAI), where the reflection of solar radiation on small aerosols is used, are widely discussed for climate mitigation (Buck and Nicholson, 2023).

The storage of pure CO_2 in geological formations in general and particularly in Germany has the disadvantage of legal restrictions, uncertain storage capacities, potential of leakage, uncertainties about its safety depending its aggregate state as well as its pressure and temperature dependence (Kühn, 2011; KSpG, 2012; Vilarrasa and Rutqvist, 2017). Additionally, negative effects can occur as a result of CO_2 interaction with ground- or seawater (Bickle, 2009; Lu et al., 2010), or the host rocks. Storage of CO_2 or carbon-rich products is crucial and particularly long-term strategy for actively removing carbon dioxide from the carbon cycle, making it a matter of significant interest. Most of these methods have an adverse socioeconomic impact as they need large areas of land and some are in conflicts with agricultural use of land or also needs a huge amount of e.g. grinded rocks where efficiencies, volumes, interactions and impact on water and biodiversity of soil seem still unclear (IPCC, 2023). All these methods and technologies described have advantages and disadvantages and - this should be highly emphasised - they are in no way intended to be a way out of further emitting CO_2, but rather a supplement to still achieve the climate targets.

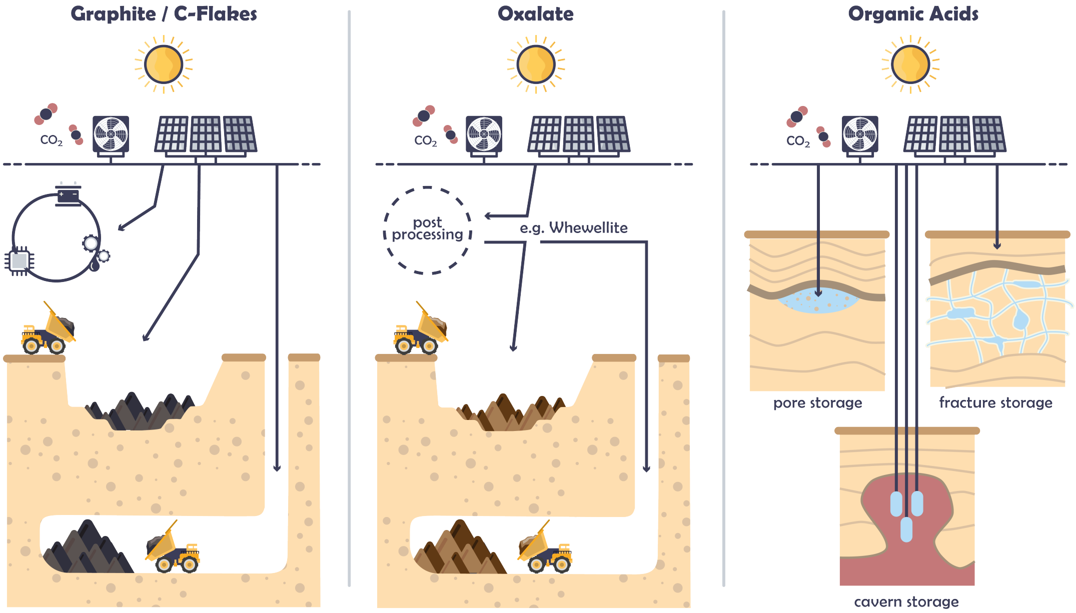

Figure 1. Final storage principle of carbon-rich products within the NETPEC framework: The captured CO_2 will be transformed into solid (graphite or oxalate) or liquid products (oxalic acid or other organic acids) using photoelectrochemical methods, where the sun is used as an energy source. The solid products can be stored in open-pit or underground mines, the liquid products can be stored within rocks having a large pore- or fracture porosity and a low-permeable structural trap and also can be stored in salt caverns.

Consequently, new approaches are being considered that complement existing methods or circumvent the fundamental problems of known methods. One of these new approaches is being investigated within the NETPEC project (www.netpec.org). It aims for the conversion of CO_2 using (photo)electrochemical methods making use of efficient, inorganic structures for light harvesting, to final products that can be stored safely in the long term (May and Rehfeld, 2019). One basic consideration of the NETPEC project is to convert the CO_2 into a liquid or solid phase as efficiently - with respect to land use - as possible. According to the principle of artificial photosynthesis in a broader sense, those photoelectrochemical methods use the sunlight as energy source to power the conversion.

Solid or liquid products whose carbon content is as high as possible are much more suitable for storage (May and Rehfeld, 2019) than gaseous products and can be in form of graphite, oxalate, oxalic acid or other carbon-rich organic acids. Since large quantities have to be stored for at least thousand years, only geological disposal seems to make sense. Promising sites for the storage of those solid products include opencast and underground mines and for fluid products, various underground storage facilities like (former) hydrocarbon reservoirs and other pore storage complexes like salt cavern reservoirs.

The aim of this work is to investigate, whether and to what extent such storage potential is available in Germany. The initial phase involves data collection with focus of the search for suitable storage areas, specifically those capable of accommodating products resulting from negative emission technologies such as NETPEC. In this exploration, various carbon-rich products, including graphite flakes (Lörch et al., 2024), oxalate, and organic acids like oxalic acid (or citric acids) were used as a reference for a product for final storage (May and Rehfeld, 2019). The storage potential can of course also be used for other products. Moreover, the option of disposing solid byproducts in regular landfills is plausible, although it won't be further explored in this study. Finally, a comprehensive assessment of the potential for Germany is carried out based on the database created. This work thus represents a so far nonexistent summary of fundamental potentials in Germany for a storage of diverse products that qualify as carbon-rich. To effectively address these partly novel technologies, establishing a comprehensive database of potential final disposal methods for both liquid and solid products become a crucial foundation. The database also serves as a foundation for informing, decision-making and ensuring effective implementation of carbon storage initiatives.

2 Storage Principle

2.1 Geological storage of carbon-rich products

Due to restrictions on the permanent storage of pure carbon dioxide, particularly in Germany due to the currently valid Carbon Dioxide Storage Act (KSpG, 2012), which imposes limitations on maximum storage volume and licensing conditions, the NETPEC project proposes a commitment to a carbon-rich solid or liquid phase that is geologically stored (Fig. 1). Solid products can be stored in open-pit or underground mines, while liquid products can be stored within rocks that have large pore or fracture porosity and a low-permeability structural trap, as well as in salt caverns.

In general, geological subsurface and surface areas - particularly old mining sites and mining related areas in Germany - show promise for accommodating several products. Especially in terms of secure storage, alternative carbon-rich products such as graphite, oxalate are suitable for a simple disposal because of their chemical harmlessness. In terms of pure CO_2 insecurities rise in regard to leakage as well as temperature and pressure stability (Aust and Kreysing, 1978; Kühn, 2011; Lübben and Leven, 2018). To uphold the principle of managing waste and emissions generated within the country, rather than burdening other less advantaged nations, the NETPEC project outlines plans to manage the product of its negative emissions technology within Germany. Additionally, the disposal and final storage of individual substances must logically deal with the potential deposition quantities of the respective substance in the first step, in addition to legal principles. As an international target till the year 2050, the NETPEC project assumes a quite common used reference goal of 10 Gt CO_2 per year of negative emissions worldwide (Anderson and Peters, 2016; May and Rehfeld, 2019). On a national basis, this would mean a mass of 146 million tons of pure carbon dioxide for Germany, which is responsible for 1.46% of global emissions (Martin et al., 2023). The masses (and volumes) can then be determined for the respective products that would have to be disposed annually. In regard to the annual extraction of mineral (i.e. non-renewable) raw materials in Germany a comparison with the emissions that Germany produces can be found in Sect. 2.6.

2.2 Materials for long-term storage

Within the NETPEC approach, the process generates carbon-rich product alternatives with notable efficiency, including graphite flakes, oxalate or organic acids such as oxalic acid or citric acids (Table 2; May and Rehfeld, 2019). The emphasis is on creating materials that can serve as effective and secure carbon sinks, addressing challenges associated with traditional storage methods (May and Rehfeld, 2019). To conduct a comprehensive comparison, factors such as the qualitative and quantitative potentials of storage, the longevity of storage, and potential interactions with the environment must be considered. NETPEC products envisages advantages in terms of safety, sustainability, and storage efficiency when compared to traditional options like pure carbon dioxide (Table 1). With the Carbon Dioxide Storage Act of 2012, however, the underground, container-less storage of pure CO_2 and its associated gases is very restrictive and also left to the individual regulations of the federal states. Apart from a few exceptions, storage of pure carbon dioxide in Germany is therefore more likely to be prohibited under the current legal situation (KSpG, 2012), albeit the law has recently been reviewed, and the removal of existing limitations is being considered (Borchers et al., 2024).

Graphite in form of carbon flakes is a product whose chemical properties are very well suited for long-term safe storage. Graphite is insoluble in water, heat- and pressure-insensitive (European Chemicals Agency, 2022) and therefore resistant to direct interactions as well as temperature- and pressure-induced influences.

Oxalate and oxalic acid in both solid and liquid forms, are considered to pose minimal concern for final disposal (Federal Environment Agency Germany, 2017). Solid oxalate has relatively low solubility in water, and aside from its acidity, its properties appear to be unproblematic. Additionally, oxalate naturally occurs as (rare) minerals in form of Whewellite or Weddellite (Hofmann and Bernasconi, 1998; European Chemicals Agency, 2022). Oxalic acid is used in sectors like building, construction, and the production of chemicals and metals. Environmental release can occur from industrial uses, including processing aids, intermediate manufacturing steps, article production, and mixture formulation (European Chemicals Agency, 2022). In addition to final disposal, recycling into industry is also feasible by utilizing graphite as well as oxalic acid as raw materials.

Both, potential areas for solid or liquid materials (and gaseous), with locations suitable for gaseous phases potentially serving for liquid storage as well are presented. The specific suitability of each site depends on the local geological characteristics of the repository and of course the product itself and is focus of further investigations and studies within the project.

Table 2. Different possible products for long-term storage, their important characteristics, and estimated masses and volumes based on the NETPEC approach for the annual conversion of globally 10 Gt CO_2.

Product	**State of matter**	**Characteristics**	**Critical aspects**	**Formula**	**Mass [Gt]$_a$**	**Volume [km^3]$_a$**
CO_2	Gaseous	Pressure and Temperature Dependence$_b$	Leakage, Legal Restrictions	CO_2	10.00	14,3$_d$
Oxalic Acid	Liquid	Acidity, Harmfulness on Groundwater, Solubility$_c$	Groundwater interactions, Leakage, Disposal Regulations	$H_2C_2O_4$	10.23	6.19
Carbon/Graphite	Solid	None$_c$	None	C	2.72	1.21
Oxalate (Ca-Oxalate)	Solid	Solubility$_c$	Groundwater interactions, Disposal Regulations	CaC_2O_4	14.55	5.60

$_a$ Resulting from 10 Gt CO_2, $_b$Vilarrasa and Rutqvist (2017), $_c$May and Rehfeld (2019), $_d$Kühn (2011), in 2.5 km depth

2.3 CO_2 emissions of Germany

In 2022, global greenhouse gas emissions reached 53.79 million tons of CO_2 equivalent, with the European Union (EU27) ranking fourth overall, contributing 37.15 gigatons of CO_2 equivalent. Among the EU27 countries, Germany ranked twelfth (Martin et al., 2023), accounting for 1.46% of the world's total greenhouse gas emissions that year (Martin et al., 2023).

In 2022, CO_2 remained the dominant greenhouse gas Germany emitted, constituting 89.5% of emissions, primarily from fossil fuel combustion. Methane emission made up 6.1%, and nitrous oxide emission comprised just under 3.1%, with agriculture being the main contributor (Fed, 2023).

2.4 Mineral extraction of Germany

Germany, as one of the leading industrial nation, is a significant consumer of mineral resources (Bastian et al., 2023). While a considerable portion of required resources, especially gravel and sand for construction purposes, is sourced domestically from open-pit mines and quarries, the country also operates several underground mines. This ensures self-sufficiency in these resources, but metals, certain industrial minerals, and energy resources, excluding lignite, heavily rely on imports (Bastian et al., 2023). On a global scale, Germany maintains its status as a prominent mining country, ranking second for lignite, third for raw kaolin, and fourth for rock salt production in 2020 (Bastian et al., 2023). In Germany, 582 million tons of just mineral raw materials were produced in total (Bastian et al., 2023).

2.5 Fossil fuel production

The extraction of fossil fuels amounted to 139.13 million tons in 2022 in Germany (Bastian et al., 2023). Despite a decline in production, lignite remains a significant indigenous fossil fuel (Bastian et al., 2023). In 2022, 130.8 million tons of lignite, 1.7 million tons of crude oil, 5.5 billion m^3 of natural gas, petroleum gas and mine gas and up to 4.8 million m^3 of peat were produced in Germany (Bastian et al., 2023).

In the 2022 report on oil and gas exploration and production in Germany, a decrease in exploration licenses was observed, with the total licensed area diminishing by 5,700 km^2 to 19,400 km^2. Although only two new exploration licenses were issued, drilling activity saw a significant increase, with drilling meterage rising by approximately 75% to 15.13 km during that year (Bastian et al., 2023). Gas production fell by 7.9% to 5.2 billion m^3 (V_n - norm cubic volume), and oil production decreased by 5.9% to 1.7 million tons (including condensate). Gas reserves declined by 4.2 billion m^3 to 38.1 billion m^3, whereas oil reserves slightly increased by 0.9 million tons to 23.8 million tons. Additionally, the available working gas volume in underground storage reservoirs dropped by 0.4 billion m^3 to 22.9 billion m^3, with plans to augment it by 3.8 billion m^3 in the future (Bastian et al., 2023).

2.6 Emission vs. Mining

If something is to be stored (below-ground), then the required volume must also be available, or be released annually. How much space or volume is available or created in Germany per year is a decisive factor in determining the general quantitative potential using this approach. For this reason, the annual extraction in the federal states and in Germany as a whole were compared with the emissions of the federal states and Germany in total. If the annual CO_2 emissions in Germany are set in relation to the production volumes of the respective federal states, the potential for storage of Germany and the individual federal states becomes clearer.

Table 3. Energy-related CO_2 emissions from primary energy consumption in 2019 and used domestic extraction of raw materials in 2019 by federal states (German Environment Agency, 2022; Statistical Offices of the Federal States Germany, 2022; Statistical Offices of the Federal Government and the Federal States, 2022). Fig. 2 visualizes the data on a map.

Federal states	Emission CO_2eq [Mio. t/a]	Extraction Fossil fuels [Mio. t/a]	Extraction Mineral raw material [Mio. t/a]
Baden-Württemberg	63.82	0.49	88.87
Bavaria	73.58	0.04	112.51
Berlin	13.68	-	-
Brandenburg	48.84	24.79	23.55
Bremen	11.44	-	-
Hamburg	14.65	-	-
Hesse	34.47	0.2^{-4}	33.13
Lower Saxony	60.15	5.57	41.12
Meckl. Western Pomerania$_a$	9.16	0.01	15.80
North Rhine-Westphalia	209.84	64.92	122.82
Rhineland-Palatinate	26.71	0.15	42.88
Saarland$_b$	21.64	0.095	2.24
Saxony	45.40	35.62	50.82
Saxony-Anhalt	24.06	6.35	47.44
Schleswig-Holstein	16.68	1.07	19.52
Thuringia	10.40	0.014	26.43
Germany	657.69	139.13	629.19

$_a$ 2018, $_b$2015

As the current data back to 2020 of the individual federal states on total CO_2 emissions are incomplete and contain all greenhouse gases emissions (including methane, nitrous oxide and fluorinated gases), data on energy-related emissions in the primary energy consumption of pure CO_2 of the year 2019 was used (Statistical Offices of the Federal Government and the Federal States, 2022) for the comparison (Fig. 2; 3).

Energy related emissions sum up to 89% of the emissions of all sectors in the last year and for the greenhouse gases, deviations of 0.2 – 4.0% from the total CO_2 emissions are to be expected on average per federal state (Statistical Offices of the Federal Government and the Federal States, 2022). For energy-related emissions of Germany as a whole and just for carbon dioxide its 658 million tons (Statistical Offices of the Federal Government and the Federal States, 2022).

190 For the Year 2022 greenhouse gas emissions (carbon dioxide, methane, nitrous oxide and fluorine gases) totaled 671 million m^3 carbon dioxide equivalent (Fed, 2023). In this sum also land use, land use change and forestry emissions are included. The volumes of (the annually) extracted raw material masses - which in Germany only for opencast mining in 2022 comprised 687 million tons of raw materials (Bastian et al., 2023) in just opencast mining. The data broken down by federal states are shown in Tab. 3.

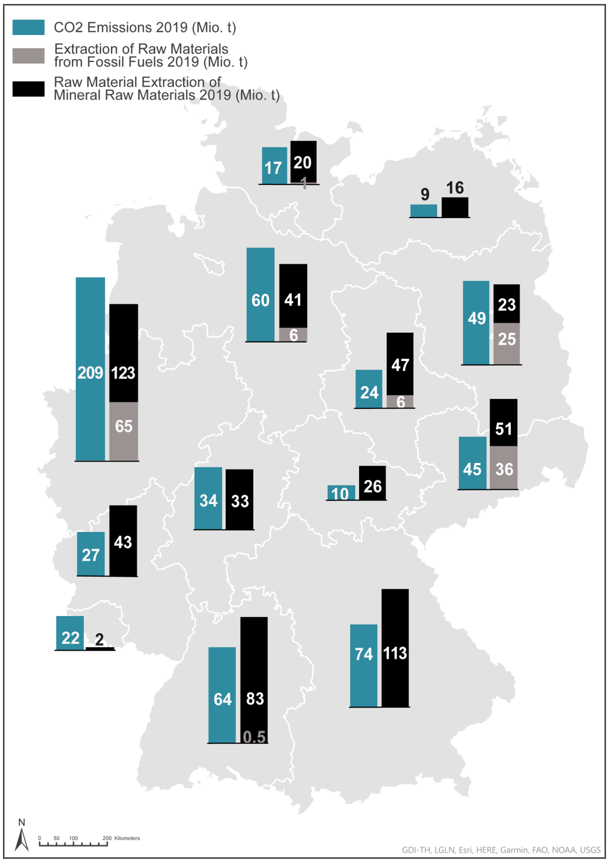

Figure 2. Energy-related CO_2 emissions from primary energy consumption versus the extraction of raw materials in Germany 2019. The city states like Bremen, Hamburg and Berlin are assigned to the surrounding federal states. Data source: German Environment Agency (2022), for details see Tab. 3.

Simplified, the extracted masses of raw materials and the total mass of greenhouse gas emissions in Germany roughly balance each other out (Fig. 2). Showing that in general the capacities of a long-term final storage of carbon-rich products is given.

3 Geology-related land use in Germany

3.1 Overview

The extraction of mineral resources in Germany falls under the jurisdiction of federal states regulations, primarily governed by the Federal Mining Act (Bastian et al., 2023). Regional authorities are tasked with granting approvals and overseeing operations. This act encompasses various resources like petroleum, natural gas, coal, ores, and others, but also includes specific regulations for certain minerals. Operations working not covered by the Federal Mining Act are subject to alternative legal frameworks, with reporting requirements applicable solely to licensed mining activities (Bastian et al., 2023). Regional disparities exist due to different factors. There are e.g., historical factors; for instance, granite extraction is governed by the Federal Mining Act only in Upper Franconia. The competent authorities responsible for permits and supervision under the Federal Mining Act are the mining authorities in each federal state (Bastian et al., 2023). Resources not addressed by the Federal Mining Act are regulated by other legal frameworks, such as the Law on aggregate mining (applicable in North Rhine-Westphalia and Bavaria), the law on the extraction of pumice stone (in Rhineland-Palatinate), and various others (Bastian et al., 2023). As a result, there is no standardized source of data on raw material production in Germany due to the existing legal framework for raw material extraction. Only companies authorized under mining law are required to report data, which they submit to the mining authorities. The federal state mining authorities compile this data and report it to the Federal Ministry of Economic Affairs and Climate Protection. Until 2017, the Ministry published this data annually in the documentation "Mining in the Federal Republic of Germany". Although this documentation has been discontinued, the data from the mining authorities is collected and used for other reports (Bastian et al., 2023).

3.2 Basis of data collection

The major goal was to set up a database of information on past, present and future mining activities in Germany to estimate the potential to store carbon-rich products in the future. The database was constructed using data provided by the geological federal states agencies of Germany. Subsequently, it is essential to highlight that the data supporting these findings are both systematically compiled by state offices and freely available. This process ensures transparency and reliability in the evaluation of Germany's capacity for storing carbon-rich products, integrating information on geological reservoirs from various sources to facilitate a comprehensive understanding of the nation's storage capabilities. Followed by an assessment of the overall potential for carbon and carbon-rich product storage.

State offices were requested regarding the availability of data pertaining to open-cast and/or underground mines, and whether such data could be utilized for constructing the described database. The majority of the data was accessible in digital formats,

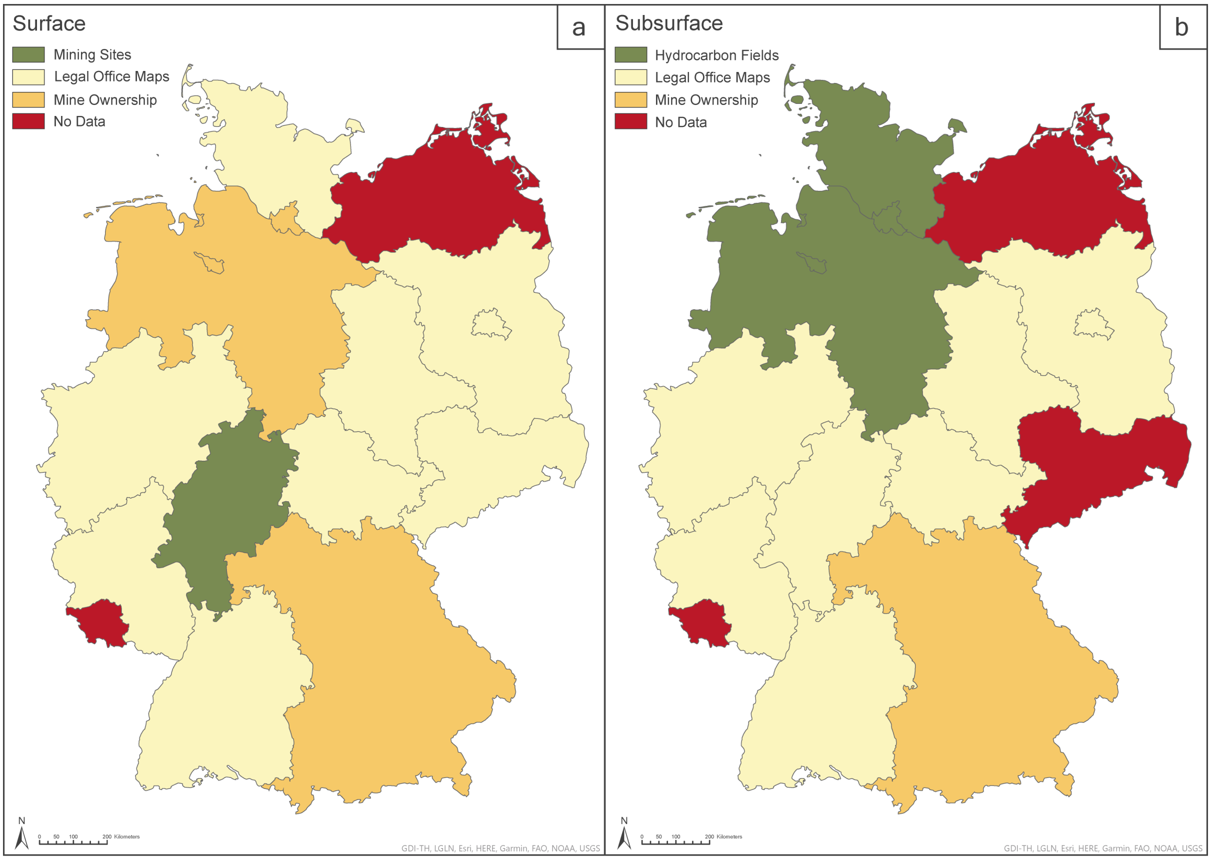

Figure 3. Data availability of mined regions of the federal states in Germany. (a) Data availability for surface mining regions, and (b) data availability of underground mining activity.

such as shape files or raster data. The raster data predominantly resided on web map servers, presenting a basic raster representation devoid of substantive content. Additional information was also be sourced from public resources like geological reports or publicly available web services/maps.

In the federal states of Mecklenburg Western Pomerania and Saarland, it was not possible to acquire information regarding potential surface and subsurface areas. Just for subsurface areas, it was not possible to receive any data for Hesse (excluding additional information of diverse drillings) and Saxony. The reasons for not obtaining any data included the enormous amount of research and digitization work and the associated costs. Additionally, in some instances, the data either no longer existed or was unavailable. Figure 3 displays the spatial availability of the data. The data predominantly includes official maps related to mining authorizations, particularly for open-cast mines and mining operations. However, due to legislative disparities and differences in data collection efforts, obtaining a uniform and comprehensive data set from all federal states proved challenging.

While the database furnishes an overall evaluation of storage potential in Germany and provides specific details about various sites, it cannot definitively determine the overall suitability of these locations for specific products. This limitation is not only due to the aforementioned reasons but also because suitability depends on the specific products to be stored, and each location exhibits significant variations in hydrological and hydrogeochemical characteristics.

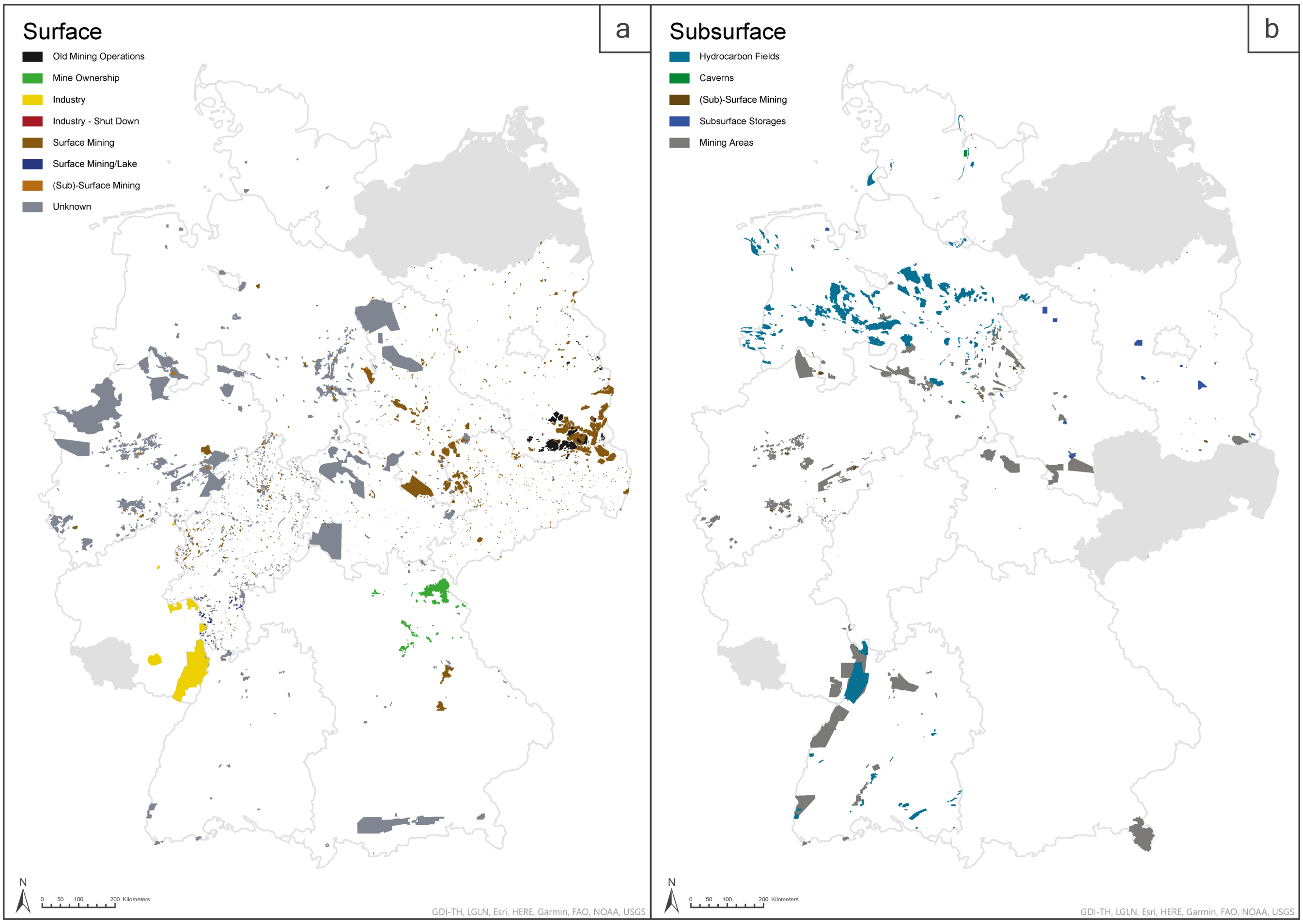

Figure 4. Map of Germany showing the regions of different mining related usage for (a) the surface and for (b) in the subsurface. The specific areas for the surface regions are provided by table 6 and for the subsurface regions by table 8. No data available for grayed out federal states.

3.3 Data base

Given the German context of the project, the database uses original German terms and regulations, with key details translated into English. Initially created as an .xlsx file, the database was structured into themed spreadsheets to provide a clear overview and differentiation of data and its origins.

The official maps contain raster information showing currently valid areas for mining permissions. In certain regions, there were distinct authorizations for mining different materials at the same time, which led to overlapping data with varying characterizations. The available raster data from WMS (Web Map Server) files was digitized into shapefiles using ArcGISPro.

Since the data primarily came from WMS and shapefiles (see Table 4) for geoinformation systems, an initial ArcGISPro project was created, using the WGS 1984 coordinate system. The data was merged to create a comprehensive view of Germany, with specific subcategories. Additionally, supplementary information from annual reports on individual mining districts was integrated into the digitized official maps where possible.

There were significant differences in data scope and availability between surface and subsurface areas. Annual production volumes from open pits and mines were sourced from respective annual reports or information services, when available (State Office for Mining, Energy and Geology - Germany, 2023). This data could potentially assist in assessing the feasibility of storage based on the yearly production outputs relevant to future NETPEC goals. The database spreadsheets are organized according to corresponding reservoirs for both surface and subsurface storage. Hydrocarbon fields data is sourced from the "Storage Cadastre of Germany" (Reinhold and Müller, 2011), which originally distinguished between crude oil, natural gas, and crude oil gas fields, but is now implemented in the subsurface storage spreadsheet. Additional data sheets are derived from the specific federal states, containing WMS information supplemented by data from federal offices. However, due to the heterogeneous nature of the data, full standardization was not always possible.

3.4 Restructuring of the data

To ensure a comprehensive database, fields got assigned in super-ordinate categories (Table 5) based on the important subjects for the assessment of storage potentials of this study, including two generated fields to differentiate between surface and subsurface areas and raw material types broadly. Due to the diverse data sources, the database comprises numerous fields, some of which contain empty cells. The category of raw material type is categorized into variable and non-variable solid rock, cohesive and non-cohesive unconsolidated rock, organic raw materials/coal, metal raw materials/ore, salts/brine, hydrocarbons, and other types of underground storage facilities with unknown content. Properties such as variability in the host rock or raw material are crucial considerations for final disposal, influencing the choice of differentiation. For the fields containing the status of the respective authorization or the status of the sites, a super-ordinate distinction into active raw material extraction, former raw material extraction, potential raw material extraction and unknown was made (Table 5).

4 Results

4.1 Storage potentials in Germany

In general, the shown results lead to a widespread potential of areas in Germany, where future storage of carbon-rich products either solid or liquid (or also gaseous) is possible. From the given data, there is no specific federal state with higher potential excluding northern states in regard to a better cavern/hydrocarbon field situation and with that a higher potential for the storage of liquid products. In some cases, like Bavaria, the limited sites and areas result from lack of data. Since the distribution of areas and thus storage potential is spread over the whole of Germany, decentralized storage is possible for future disposal. This not only makes it possible to offset regional emissions by storing the end products, but also to integrate the technology at the

Table 4. Data availability and quantity of the Federal States

Federal States	Data Type	Informations
Baden-Württemberg	wms	Freiburg Regional Council State Office for Geology, Raw Materials and Mining LGRB-BW LBD: Mining (RISBinBW)
Bavaria	shape-files	Bavarian State Ministry of Economic Affairs Regional Development and Energy
Berlin	wms	INSPIRE ST AM
Brandenburg	wms	INSPIRE ST AM Brandenburg State Office for Mining, Geology and Raw Materials (LBGR)
Bremen	shape-files	NIBIS® KARTENSERVER Lower Saxony Soil Information System
Hamburg	shape-files	NIBIS® KARTENSERVER Soil Information System of Lower Saxony
Hesse	shape-files	Hessian State Agency for Nature Conservation Environment and Geology
Lower Saxony	shape-files	NIBIS® KARTENSERVER Soil Information System of Lower Saxony
Mecklenburg-Vorpommern	–	–
North Rhine-Westphalia	shape-files	Arnsberg District Government; Federal State of NRW
Rhineland-Palatinate	wms	INSPIRE ST AM
Saarland	–	–
Saxony	wms	State-owned enterprise Geobasis Information and Surveying Saxony (GeoSN), INSPIRE SN Mineral resources; Fossil Fuels Geoportal Saxony
Saxony-Anhalt	wms	INSPIRE ST AM; Geoportal Data Service Saxony-Anhalt State Office for Geology and Mining Saxony-Anhalt (LAGB); Mining and Raw Materials in Saxony-Anhalt Inspire Geodata Portal Saxony-Anhalt (LAGB)
Schleswig-Holstein	-	-
Thuringia	shape-files	Thuringian State Office for the Environment, Mining and Nature Conservation

respective locations if necessary, thus eliminating supply routes and chains and thus further emissions. Germany is currently planning the development of a new CO_2 distribution network, which will require substantial investment (OGE - Open Grid Europe, 2024). However, this project will incur significant costs and generate additional emissions during its implementation. By implementing local storage solutions, the need for extensive network expansion can be minimized. Since storage potential

Table 5. Data Assignment

Status	Assigned as	Description
Type of Raw Material	Active RMP	Type of Raw Material excavated/mined
Legally Valid	Active RMP	Legal valid excavation
Mine Ownership	Active RMP	Legal Mining authorization and ownership actual excavation included
Maintained Land Ownership Rights	Active RMP	Legal Mining authorization and ownership actual excavation included
Authorization	Active RMP	Legal Mining authorization and ownership actual excavation included
Old Mining Operations	Former RMP	Former mining operations and excavation
Type of Raw Material - expired	Former RMP	Former mining operations and excavation for described type of raw material
Area of Near-Surface Deposits	Potential RMP	Deposits of raw material no authorization, no excavation (yet)
Authorization (§ 8 BBergG)	Potential RMP	Permission to explore and exploit raw material deposits mining not mandatory included
Authorization (§ 7 BBergG)	Potential RMP	Permission to explore and exploit raw material deposits mining not mandatory included
Area for the Extraction of Near-Surface Deposits	Potential RMP	Permission to explore and exploit raw material deposits mining included
Permission for commercial purposes	Potential RMP	Permission for commercial purposes mining not mandatory included
Permission for large-scale exploration	Potential RMP	Permission to explore and exploit raw material deposits
Unknown	Unknown	Unknown

*RMP = Raw Material Production

is distributed across Germany, decentralized storage options are feasible for future disposal. This allows regional emissions to be offset by storing carbon-rich end products locally. Additionally, it opens the possibility of integrating negative emission technologies at specific sites, thereby reducing the need for extensive supply routes and chains, further cutting associated emissions.

In the following, a distinction is made between potential on the surface and in the subsurface; maps were created for the individual categories for better visualization.

4.2 Storage potentials at the surface

As investigated previously, based on whole state data (Sect. 2.6), there is a large potential for the final disposal of carbon-rich products in Germany. However, the situation for such disposal is not only good in terms of the available areas, but also in terms of the mass and volume of the potential substances in regard to the available volumes. Areas for potential surface storage is shown in figure 6, with an area up to 99,000 km^2 with different use/authorizations. It's important to note that this figure doesn't precisely reflect the practical/effectively usable space, given the necessity to account for double entries due to diverse permits and also areas with just the permission and no actual mining (See Sect. 3; table 6). Especially when dealing with final products that could lead to interactions with the host rock, the potential areas were divided into the extracted raw materials at that area that will deal as a repository too. For surface locations metal raw materials and/or ore turned out to be the largest in terms of potential surface area with 61,870 km^2, followed by an unknown mining related use of the areas and organic raw materials with 7,010 km^2 (Table 6 and 7).

Table 6. Surface areas related to mining related usage in Germany. The spatial distribution is shown in Fig. 4 a.

Classification	Area [km^2]
Old Mining Operation	1,270
Mine Ownership	1,500
Industrial Operation Areas	3,940
Surface Mining (inactive and active)	12,110
Unknown	80,440
Total	99,260

Table 7. Surface authorization areas of most common types of raw materials related to mining usage in Germany. The map in Fig. 4 a displays the spatial distribution of the classes.

Classification	Area [km^2]
Metal Raw Materials/ Ore	61,870
Solid Rock - non alterable	550
Solid Rock - alterable	6,810
Loose rock - cohesive	110
Loose rock - non cohesive	3,040
Organic Raw Materials/Ore	7,010
Unknown	19,870

4.3 Storage potentials in the subsurface

The CO_2 storage potential of the geological subsurface in Germany has been evaluated several times and over many years depending on the research focus, and amounts in deep saline aquifers (on- and offshore) of 20 to 115 Gt, in depleted oil-gas fields 2.75 Gt and in depleted oil-fields 130 Gt (Hilgers et al., 2024). As the same challenges as with mining areas in general appear (see Sect. 3) the overall potential in Germany still seemed not clear in detail. The database could show that concerning subsurface locations intended for storing potential liquid end products, there are areas that expanses totaling up to 35,000 km^2 (Fig. 8) for potential storage. In Germany, subsurface areas are authorized for different raw materials related to mining. Metal ores are found in large regions, while hydrocarbons like oil and gas cover even more extensive areas. Salt and brine extraction is also significant, while coal mining occupies a much smaller area, some areas with unknown authorization remain (Table 7). Disregarding the findings of the "Storage Cadastre Germany 2024" which conducted extensive research on pore complexes that could also be relevant for carbon-rich liquid and gaseous products, the potential for subsurface storage remains highly promising (Kühn, 2011). Also, when focusing solely on potential and examining individual sites, we can estimate that a solitary cavern, expanded to the dimensions of a production cavern filled in this manner, possesses a cavity volume of approximately 1 million m^3 (Salzgewinnungsgesellschaft Westfalen mbH & Co. KG, 2021, personal communication). The 114 caverns of Salzgewinnungsgesellschaft Westfalen mbH & Co. KG can therefore be used to illustrate the potential for the final disposal of a product, even if future conflicts with regard to hydrogen storage must admittedly be taken into account here and will be discussed later on.

Table 8. Classification of subsurface areas of to mining related usage in Germany. The spatial distribution is visualized by Fig 4 b.

Classification	Area [km^2]
Hydrocarbon Fields	16,530
Caverns	2,220
Other Underground Storage	640
Mine Ownership	22,750
Unknown	760
Total	34,800

4.4 Maps

The map depictions show the area-related potential for storage and were separated in regard to their storage related topics as well as in surface mining or surface locations and underground mining or subsurface locations. As a rule, an authorised and exercised mining operation does not cover the entire area shown, which is why only an estimate of the potential was made in this chapter. The areas shown may occur twice due to different forms of authorization.

Table 9. Subsurface authorization areas for raw materials related to mining related usage in Germany. Fig 4 b shows the spatial distribution of the region on a map.

Classification	Area [km^2]
Metal Raw Materials/ Ore	10,860
Solid Rock - alterable	910
Hydrocarbons	16,530
Salt/Brine	13,130
Coal	180
Underground Storage	160
Unknown	760

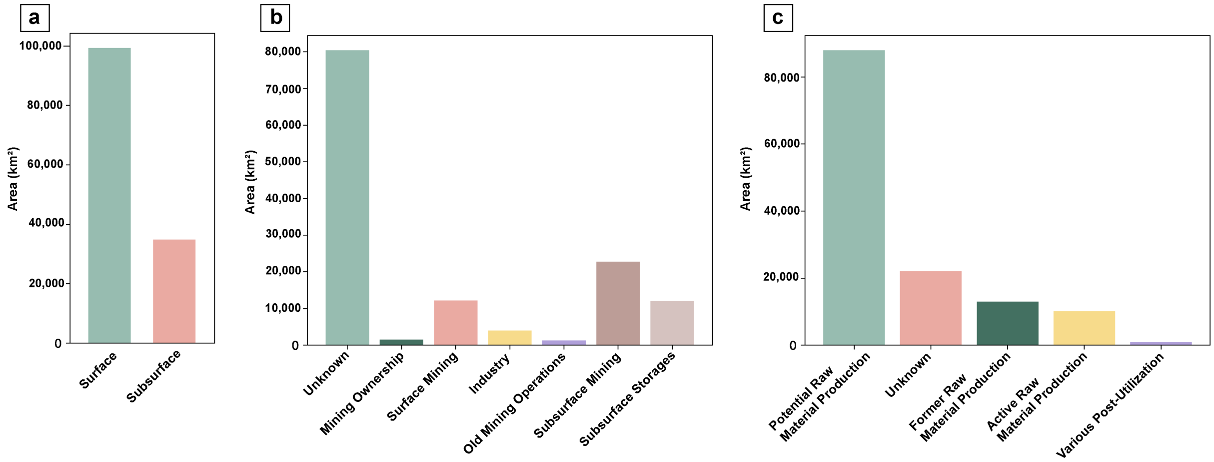

Figure 5. Areas of localities for potential storage facilities, differentiated by their type and status. The pie charts show the area of mining-related land in Germany. (a) Distribution of the area of surface and underground sites. (b) Distribution of types of sites based on their area. (c) Status of the different sites based on their area.

The division described in this chapter is shown in the respective maps (Figs. 6 and 7) and illustrates the reasons for such a division. Depending on the geology, different areas become visible. In the north of Germany, the capacities for underground storage of products are more desirable as reservoirs and caverns are already being generated here due to the hydrocarbon deposits.

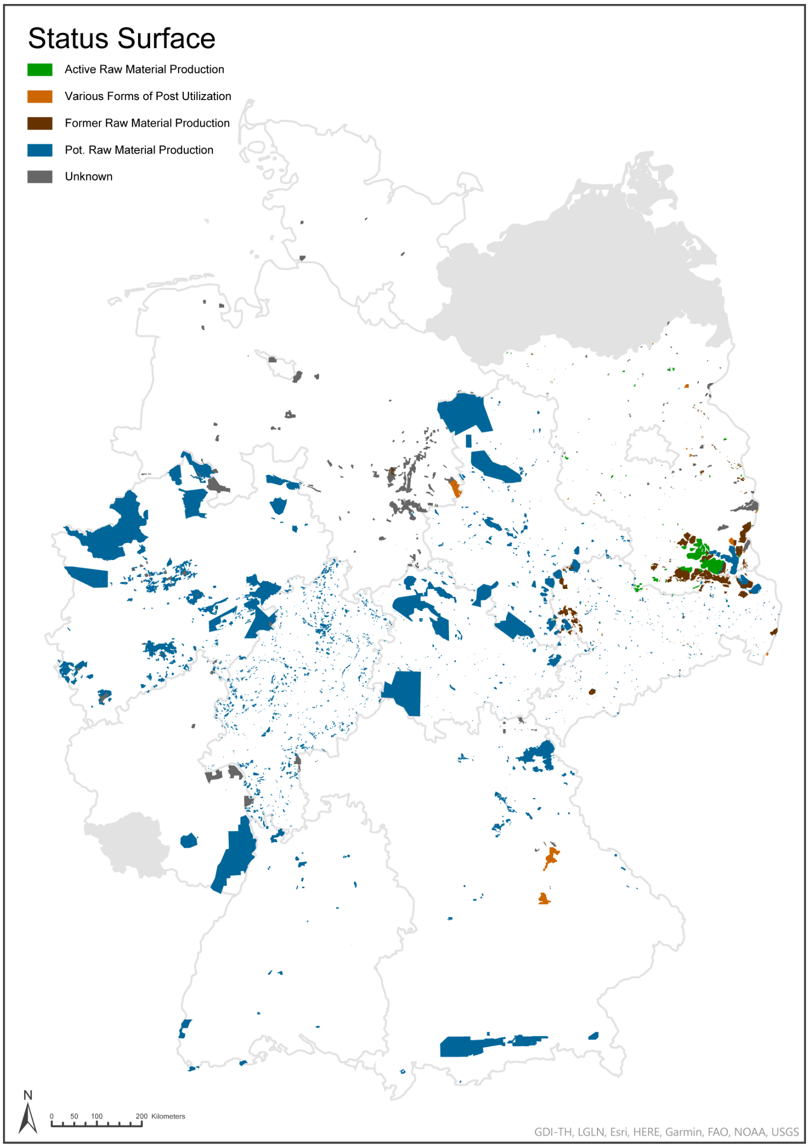

Figure 6. Map of Germany depicting mining-related surface areas, categorized by status. No data available for grayed out federal states.

5 Estimation of storage potentials

As the data base only provides areas and little about overburden and volumes, a rough estimation of potential volumes will be made in this chapter, based on the geological reports and average densities of the most commonly extracted raw materials and average thicknesses of rock strata. In case of the NETPEC project the different final products generate different masses within the conversion from carbon dioxide that are needed for net-negative emissions. For these masses the goal of 10 Gt CO_2 that are extracted from the atmosphere (Anderson and Peters, 2016) was used to calculate the specific masses resulting from the

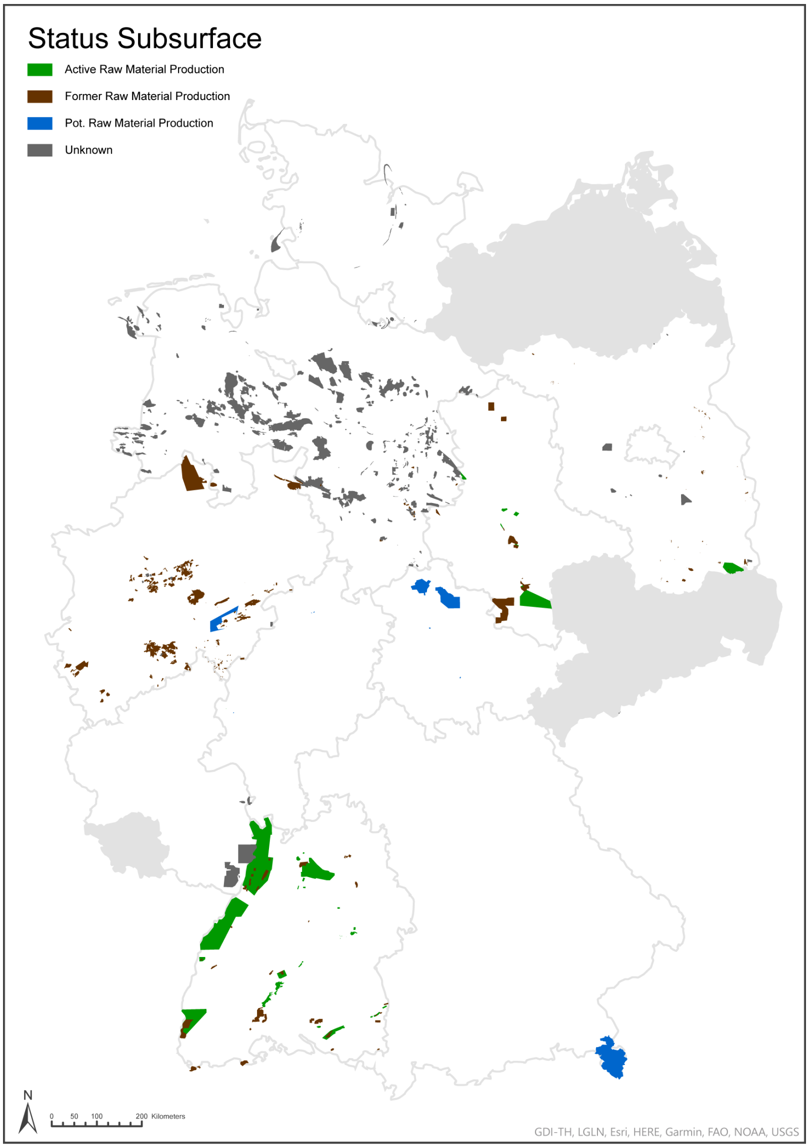

Figure 7. Map of Germany depicting mining-related subsurface areas, categorized by status. No data available for grayed out federal states.

conversion (2). For graphite, the process will result in 2.72 Gt worldwide per year, for (Ca-)oxalate it will result in 14.55 Gt and for oxalic acid it will result in 10.23 Gt per year (Table 2, which then can be then used for a rough estimation of the storage potentials in Germany.

Assuming that only 1% of the mining-related areas would be suitable for final disposal of carbon-rich end products, a total 335 of 990 km^2 would still be available on the surface and 348 km^2 in the subsurface. That means just for surface disposal, there would be an area available that is larger than the size of the city Berlin, and for subsurface storage an area that is larger than the city Frankfurt (Main). With this assumption in all cases of resulting final products Germany shows the potential for final storage.

To better understand the requirements for storing these materials, the thickness of surface and subsurface layers was estimated based on the available areas and the volume of products (Table 2, Fig. 8, Fig. 9). Graphite, for example, would require surface layers ranging from about 2 meters thick at small areas, down to less than 0.5 meters as the area increases, given a total volume of 1.21 km^3 for a negative emission goal of 10 Gt . For calcium oxalate, which involves a larger volume of 5.6 km^3, the surface layer thickness also decreases as the area increases but would stay larger then the thickness of graphite. These surface thickness estimates suggest that even with substantial areas available for disposal, the layers of material would remain relatively thin.

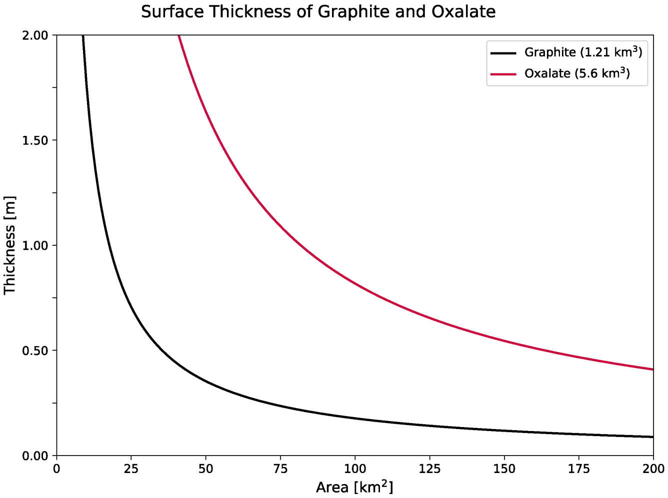

Figure 8. Estimated surface thicknesses required for final storage of carbon-rich products, including graphite and oxalate based on available surface areas if 10 Gt of CO_2 would be removed from the atmosphere and converted in this products. The surface thickness plot shows the relationship between area and thickness for graphite (1.21 km^3) and oxalate (5.6 km^3). As area increases, the required thickness of material decrease.

For subsurface storage (Fig. 9), the scenario is somewhat different. The estimated reservoir thickness for CO_2 starts at about 20 meters for smaller areas and decreases as the area grows, based on a total volume of 14.3 km^3. Similarly, oxalic acid, with a volume of 6.19 km^3, requires a similar initial thickness which diminishes with increasing area. These underground thicknesses are notably larger than the surface layers due to the greater volumes for the given products.

These estimations, considering both surface and subsurface storage, illustrate that while surface disposal requires thinner layers for products like graphite and oxalate, subsurface storage for the given products would demands considerably thicker layers, particularly for CO_2 and oxalic acid. Nonetheless, Germany's available surface and underground areas provide substantial capacity to store the required volumes of final products, ensuring the feasibility of final storage for these carbon-rich materials.

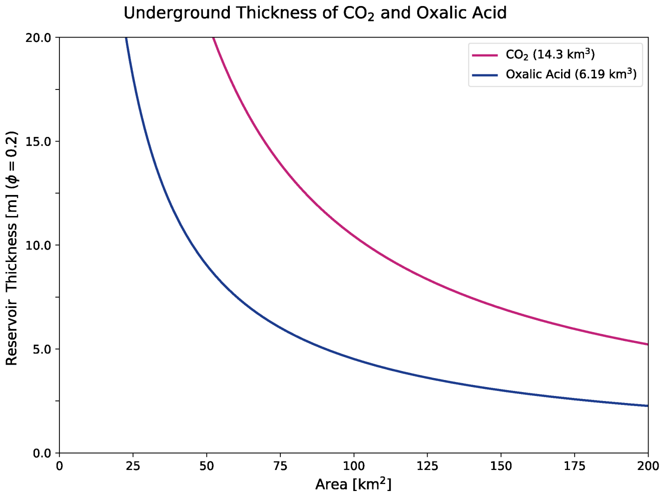

Figure 9. Estimated underground thicknesses required for final storage of carbon-rich products, including CO_2 and oxalic acid, based on available subsurface areas if 10 Gt of CO_2 would be removed from the atmosphere and converted to those products. The underground thickness plot shows the relationship between area and thickness for CO_2 (14.3 km^3) and oxalic acid (6.19 km^3). As area increases, the required thickness of material decreases, with subsurface storage requiring significantly thicker layers compared to surface disposal (Fig. 8). The volume of 10 Gt CO_2 when stored at a depth of 2.5 km was used (Kühn, 2011).

6 Discussion

6.1 General aspects for final storage of NET-products

There have been several attempts to estimate the amount of CO_2 which can be stored in the future in the underground (Reinhold and Müller, 2011). Storing pure CO_2 underground through carbon capture and storage (CCS) has several drawbacks. Next to temperature and pressure stability (Kühn, 2011; Vilarrasa and Rutqvist, 2017), key concerns include the risk of leakage, where CO_2 could escape through geological faults or old well bores, posing environmental and safety risks (Aust and Kreysing, 1978; Markus and Schaller, 2024). Additionally, injecting CO_2 can cause induced seismicity, potentially triggering earthquakes in geologically active areas (Zoback and Gorelick, 2012).

However, this is the first study, which attempts to quantify the potential to store solid or fluid carbon-rich products (graphite, oxalate and oxalic acids) instead of (pure) and gaseous CO_2. This first attempt shows, that the storage capacity for such products is given. However, the study has some limits, which will be discussed below.

6.2 The concept of the NETPEC project

The NETPEC project currently represents a very exploratory approach, aiming to extract carbon dioxide from the atmosphere to convert it by the use of solar radiation as the energy source into ideal energetically optimized products that can be stored safely in the long term. The conversion of CO_2 into a product has been demonstrated at laboratory level (Esrafilzadeh et al., 2019; May and Rehfeld, 2019; Lörch et al., 2024), but is not yet applicable in larger dimensions. The same applies to the costs incurred both in up-scaling and within conversion. The influence of the panels on local climate events is also currently under investigation as part of the project. Feasibility studies are underway to clarify the actual NET negativity.

6.3 Storage concept and legal aspects

Re-purposing former mining sites for the storage of products from NET's presents various advantages. Some sites come equipped with existing infrastructure, such as shafts and tunnels, that can be repurposed, reducing both costs and the time needed to establish a storage facility. Moreover, utilizing the expertise already present in these regions aids in effective monitoring and ensures the long-term safety of the storage.

When considering the storage of a substance from the conditioning of CO_2, the legal aspects of waste disposal and further legal aspects of landfill must be taken into account. In the case of a solid end product that is to be stored; it is a matter of waste disposal from a legal point of view. The legislator differentiates between the utilization of waste and its disposal (DepV, 2009; KrWG, 2023, German Landfill Regulation). In mines, which are subject to mining supervision, the utilization of waste for the filling of excavation areas is possible, provided that a corresponding permit is available. The extensive and federal state-dependent set of rules and regulations also play a further role in this context.

The re-utilization aspect results from the use of the waste volume within the scope of the reclamation required by mining law and presupposes that the waste is considered harmless. However, the framework conditions for such waste re-utilization are very restrictive. On the one hand, the acceptability of the acceptance option (apart from individual cases due to existing grandfathering regulations) is limited to the waste "soil and stone", and on the other hand, limit values are defined for all relevant material parameters, which are based on the requirements of the Soil Protection Law (DepV, 2009, German Landfill Regulation). The use of opencast mining areas after the end of the mining jurisdiction requires, depending on the federal state, an approval procedure under Landfill Law or Soil Protection Law (DepV, 2009; BBodSchV, 1999). The subsequent landscape of mining use must be designed in an unrestrictedly targeted manner based on the requirements of nature conservation law in the sense of nature conservation-oriented development (BBodSchV, 1999, Soil Protection Act).

A harmlessness of the waste is given for the NETPEC products graphite and oxalate in the broadest sense, but needs to be investigated further in the future. With every other products of course it is a subject to the listed regulations but focusing on NET-products and educts, there is a huge potential of final storage given in Germany. A redesign, especially in the sense of a nature conservation-oriented development of the opencast mining areas, is given in particular for graphite, since here a similar product is introduced as the extracted raw material - in the same sense as the idea of Thengane and Bandyopadhyay (2020) of "biochar mines".

6.4 Data

The establishment of a database for the storage of products from NET's in old mining sites is a crucial component of this initiative. However, certain challenges and limitations arise in managing and utilizing the available data. In many cases, data sets are incomplete, providing limited information on volumes, and the activity status of these sites is often uncertain due to legal mapping issues. Some of these areas might be in subsequent use, with most of the information remaining unknown.

The most significant challenge is the lack of up-to-date information in regulatory maps. These maps, intended to guide the regulatory aspects of storage, quickly lose their relevance, making it difficult to rely on them for accurate and current data. In summary, they face two challenges: frequent updates, occurring annually due to their rapid obsolescence, and the absence of detailed information on actual mining activities, extraction volumes, raw materials and overburden at the sites. This issue underscores the importance of maintaining a dynamic and regularly updated database to ensure the effectiveness of storage management in these mining related sites and areas. Additionally, the regulatory landscape for disposal and final disposal often varying by federal state. Incorporating these challenges into the discussion is essential for a comprehensive understanding of the complexities associated with re-purposing old mining sites and/or mining related areas for storage. The establishment of a well-maintained database becomes even more critical in overcoming these hurdles, providing accurate and updated information to support decision-making, regulatory compliance, and community engagement. Successful implementation of the storage initiative necessitates addressing these data-related challenges alongside other considerations such as community perceptions, possible interactions of products and repository and more.

6.5 Uncertainties in land use status

The land use of the areas in this study is often unclear or unknown and show different uncertainties. This is based on different data sets as well as different archiving and documentation of such data (see Sect. 6.3). Since the data comes from the state offices and public authorities in the areas of nature conservation, environment and geology, the use of the unknown areas is at least certain in the area of mining or mining-related use. The authorizations and permits described above and their differentiation do not generally indicate actual mining (Table 5).

This results in uncertainties and inaccuracies which, however, are negligible for the presentation of large-scale potentials. In addition, there are several authorizations for different purposes for several areas at the same time, so that some areas are duplicated. Of course, for the statistics just single value areas were included, but uncertainties of land use status rises with unspecific status and especially uncertainties dealing with different repository types. Furthermore, the storage capacity of old mining areas and mining related areas may be limited, depending on the site's size and characteristics.

6.6 Socio-economic aspects and land use conflicts

The presented general approach, to store carbon-rich products in exploited reservoirs, aims for avoiding conflicts with other land uses, such as agriculture or urban development, addressing concerns related to competition for land resources, which leads to problems within other NET-approaches like afforestation/reforestation, peatland restoring and others. Using land for carbon dioxide removal activities can limit or increase the cost of its use for food production and environmental conservation (Markus and Schaller, 2024). The impact of CDR on land use varies based on the type, scale, and local context of the activities.

Terrestrial methods like BECCS (Bioenergy with Carbon Capture and Storage), afforestation, reforestation, and biochar production require land and may displace agriculture and forestry. Rewetting peatlands and increasing soil carbon can also reduce agricultural land availability (Borchers et al., 2024). Technical approaches such as BECCS, CCS and also the NETPEC approach require constructing large facilities and reserving land near renewable energy sources. Areas used for solar energy harvesting also represent the largest land footprint for NETPEC too, yet they still significantly require less space than bio-based methods (May and Rehfeld, 2019). Additionally, subsurface storage of these approaches storage could interfere with other subsurface activities like gas storage (H_2 or compressed air), water maintenance, and geothermal energy exploitation (Markus and Schaller, 2024). Economically, the introduction of CDR practices could reduce land availability and increase land demand, potentially raising food production costs (Markus and Schaller, 2024). Large-scale CDR activities might degrade environmental conditions, affecting soil, water, and biodiversity, thus limiting ecosystem services.

Additionally, in case of NETPEC converting CO_2 to graphite before storage not only sequesters carbon but also provides a valuable material with industrial applications, potentially generating economic value. However, geological uncertainties in some old mining areas, including risks of subsidence or faults, could compromise the containment of stored products. Another critical factor is public perception and community opposition. Communities near old mining areas and mining related areas may resist using these sites for final storage due to concerns about safety, environmental impact, and health risks. As NETPEC aims on the storage for at least 1,000 years, ideally outside the biosphere to minimize potential impact on living organisms and prevent any adverse interactions between the products and their storage repositories, it is important to also investigate potential interactions of the product and the host rock. The success of such projects relies on public acceptance, community engagement, and addressing these concerns.

6.7 Uncertainties of storage potentials

It is essential to ensure that selected sites can accommodate the volume of products that need storage. Long-term integrity and monitoring are crucial for sustaining the storage's effectiveness, and addressing potential liability issues associated with leakage or environmental impact is paramount. In conclusion, the feasibility and success of (re-)purposing mining related areas for storage depend on careful site selection, effective community engagement, and comprehensive risk assessment and monitoring measures. In case of a fluid product the hydrogeochemical reactions or influence on the surrounding reservoir and also with the groundwater must be investigated. For specific products and objectives, the database can help to asses regions rather than make an accurate specific site assessment. This assessment requires extensive research of product and repository and is not what the database is capable of.

For evaluating the uncertainties, individual uncertainties need to be taken into account. Of course, there are uncertainties in raw material excavation and excavation thicknesses that need to be regarded when further working on potential storage volumes. For potential storage and implementing the technologies also in the areas to reduce transport ways, accessibility of the areas as well as topographical factors play a role too. In regard to the database, data quality and reliability especially in regard to data which is current state and updated is a huge factor especially in the case of mining authorities.

7 Summary

Every negative emission technology that produces a carbon-rich product or byproduct must address its disposal, recycling, or final storage. Given the critical need to sequester CO_2 and keep it out of the carbon cycle for effective climate mitigation, this study highlights Germany's significant potential for the final storage of carbon-rich products in mining-related areas. This study investigates the potential for storing carbon-rich products in Germany's mining areas as a means of climate mitigation, emphasizing the critical need to sequester CO_2. A major focus of the research is the development of a comprehensive database that evaluates storage potential across the country. This database is unique in its reliance on detailed, reliable, and open-source geological data provided by the federal states, marking a significant advancement in the field. The database serves as an essential tool for identifying suitable storage sites, offering valuable insights into the geographic and geological factors that influence site selection. While it provides an evaluation of storage potential, the database also highlights that no single site is universally suitable for all types of carbon-rich products, due to variations in hydrological and hydrogeochemical characteristics. Despite these challenges, the database remains a crucial resource, enabling tailored and informed decisions for effective CO_2 sequestration. Germany's mining areas offer substantial storage capacities, making them ideal for this purpose. The availability of geological data from federal sources enhances the accuracy and utility of the database, promoting transparency and encouraging further research. The resulting database can be expanded and supplemented according to intention. It is capable of showing different potentials for storage/disposal areas in Germany and the respective area. The most detailed information was given for geological data regarding pore storage and barrier complexes in Germany of the "Storage Cadastre Germany" (Reinhold and Müller, 2011) and were provided by the Federal Institute for Geosciences and Natural Resources (BGR) and were a perfect example for freely available data that lead to further investigations and opportunities. The map applications resulting from the database can subsequently be used for different types of questions. In particular with regard to questions of land management, infrastructure and sustainable subsequent use of land without conflict in terms of nature conservation, there are far-reaching possibilities (e.g., spatial analysis for suitability maps) for using the map project. Key findings from this study include identifying significant storage capacities for carbon-rich products in German mining areas and demonstrating the effectiveness of geographical and geological factors in site selection. These findings support climate mitigation efforts by confirming the potential for effective CO_2 sequestration. The study also outlines the need for future research to focus on understanding how specific NET products (such as oxalate, graphite, and oxalic acid) interact with storage environments. This will help ensure the long-term stability and environmental safety of stored materials. The database created is freely accessible, fostering ongoing collaboration and exploration in this and related fields. Effective community engagement is recommended to maintain public support and ensure that these technologies are implemented safely and effectively.

The NETPEC project's innovative approach to carbon-rich product storage in mining-related areas offers a viable pathway for long-term CO_2 sequestration. The creation of an open-source database mapping storage potential across Germany is a crucial tool that supports ongoing efforts to mitigate climate change. By identifying and utilizing these sites, Germany could take a significant step toward achieving its carbon neutrality goals while setting a precedent for other regions globally to adopt similar strategies for carbon storage. Once again, and finally the authors would like to emphasize that the phase-out of fossil fuels and the reduction of emissions to a minimum must be the focus of climate policy and that the extraction and storage of CO_2 must be seen solely as a complementary means.

8 Data availability

The database described in this manuscript is published via the repository "TUdatalib" of Technical University Darmstadt with the DOI https://doi.org/10.48328/tudatalib-1577 (Diekmeier, S. and Reiter, K. and Henk, A. and Friebe, C. and TU Darmstadt, 2024).

Author contribution

SD contributed in data collection, restructuring, map applications and designed the figures, KR and AH did supervision of the work, SD and CF digitized the raster file data of WMS-Data, draft writing by SD and KR, SD took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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References

National Trend Tables for the German Atmospheric Emission Reporting 1990 - 2022, http://www.umweltbundesamt.de/emissionen, 2023.

Anderson, K. and Peters, G.: The trouble with negative emissions, Science, 354, 182–183, https://doi.org/10.1126/science.aah4567, 2016.

Aust, H. and Kreysing, K.: Geologisches Jahrbuch - Geologische und geotechnische Grundlagen für die Tiefeninjektion von flüssigen Abfällen, Bundesanstalt für Geowissenschaften und Rohstoffe und Geologische Landesämter Hessen, Schweizerbart'sche Verlagsbuchhandlung, 1978.

Bastian, D., Bookhagen, B., Eicke, C., Elsner, H., Henning, S., Kern, M., Kuhn, K., Liesegang, M., Lutz, R., Mählitz, P., Moldenhauer, K., Pein, M., Schauer, M., Schmidt, S., Schmitz, M., Szurlies, M., and Wittenberg, A.: BGR – Bundesanstalt für Geowissenschaften und Rohstoffe (2023): Deutschland – Rohstoffsituation 2022, Tech. rep., Bundesanstalt für Geologie und Rohstoffe, Hannover, https://doi.org/10.25928/dero-si22, 2023.

BBodSchV: Deutscher Bundestag: Bundes-Bodenschutz- und Altlastenverordnung (BBodSchV), https://www.gesetze-im-internet.de/bbodschg/BJNR050210998.html, 1999.

Bickle, M. J.: Geological carbon storage, Nature Geoscience, 2, 815–818, https://doi.org/10.1038/ngeo687, 2009.

Borchers, M., Förster, J., Thrän, D., Beck, S., Thoni, T., Korte, K., Gawel, E., Markus, T., Schaller, R., Rhoden, I., Chi, Y., Dahmen, N., Dittmeyer, R., Dolch, T., Dold, C., Herbst, M., Hess, D., Kalhori, A., Koop-Jakobsen, K., Li, Z., Oschlies, A., Reusch, T. B. H., Sachs, T., Schmidt-Hattenberger, C., Stevenson, A., Wu, J., Yeates, C., and Mengis, N.: A Comprehensive Assessment of Carbon Dioxide Removal Options for Germany, Earth's Future, 12, 1–23, https://doi.org/10.1029/2023EF003986, 2024.

Buck, H. J. and Nicholson, S.: Solar geoengineering research in the global public interest: A proposal for how to do it, One Earth, 6, 1652–1664, https://doi.org/10.1016/j.oneear.2023.11.012, 2023.

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., Fennell, P. S., Fuss, S., Galindo, A., Hackett, L. A., Hallett, J. P., Herzog, H. J., Jackson, G., Kemper, J., Krevor, S., Maitland, G. C., Matuszewski, M., Metcalfe, I. S., Petit, C., Puxty, G., Reimer, J., Reiner, D. M., Rubin, E. S., Scott, S. A., Shah, N., Smit, B., Trusler, J. P., Webley, P., Wilcox, J., and Mac Dowell, N.: Carbon capture and storage (CCS): The way forward, https://doi.org/10.1039/c7ee02342a, 2018.

DepV: Verordnung über Deponien und Langzeitlager (Deponieverordnung - DepV), https://www.gesetze-im-internet.de/bundesrecht/depv_2009/gesamt.pdf, 2009.

Diekmeier, S. and Reiter, K. and Henk, A. and Friebe, C. and TU Darmstadt: Storage potentials for carbon-rich products in Germany - Database, https://doi.org/10.48328/TUDATALIB-1577, https://doi.org/10.48328/TUDATALIB-1577, 2024.

Esrafilzadeh, D., Zavabeti, A., Jalili, R., Atkin, P., Choi, J., Carey, B. J., Brkljacˇa, R., O'Mullane, A. P., Dickey, M. D., Officer, D. L., MacFarlane, D. R., Daeneke, T., and Kalantar-Zadeh, K.: Room temperature CO2 reduction to solid carbon species on liquid metals featuring atomically thin ceria interfaces, Nature Communications, 10, 865, https://doi.org/10.1038/s41467-019-08824-8, 2019.

European Chemicals Agency: Substance Info on Oxalic Acid, https://echa.europa.eu/substance-information/-/substanceinfo/100.005.123, 2022.

Federal Environment Agency Germany: Evaluierung der Bewertungsverfahren im Kontext mit der Verwertung mineralischer Abfälle in/auf Böden - Teil I: Stofffreisetzungsverhalten mineralischer Abfälle in/auf Böden, Texts 112/2017, 2017.

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., De Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. V., Wilcox, J., Del Mar Zamora Dominguez, M., and Minx, J. C.: Negative emissions - Part 2: Costs, potentials and side effects, https://doi.org/10.1088/1748-9326/aabf9f, 2018.

Fuss, S., Canadell, J. G., Ciais, P., Jackson, R. B., Jones, C. D., Lyngfelt, A., Peters, G. P., and Van Vuuren, D. P.: Moving toward net-zero emissions requires new alliances for carbon dioxide removal, One Earth, 3, 145–149, 2020.

Fuss, S., Gruner Friedemann, and Hilaire Jerome: CO2-Entnahmen: Notwendigkeit und Regulierungsoptionen. Studie im Auftrag der Wissenschaftsplattform Klimaschutz., Tech. rep., Wissenschaftsplattform Klimaschutz, Berlin, 2021.

German Environment Agency: The Use of Natural Resources. Resources Report for Germany 2022, Yearly Report for Germany, https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/fb_the_use_of_natural_resources_2022_0.pdf, 2022.

Hilgers, C., Schilling, F. R., Hilgers, C., and Schilling, F. R.: Kohlendioxidabscheidung und geologische Speicherung (CCS) – ein Überblick, ZDGG, 175, 89–109, https://doi.org/10.1127/zdgg/2024/0435, 2024.

Hofmann, B. A. and Bernasconi, S. M.: Review of occurrences and carbon isotope geochemistry of oxalate minerals: implications for the origin and fate of oxalate in diagenetic and hydrothermal fluids, Chemical Geology, 149, 127–146, https://doi.org/https://doi.org/10.1016/S0009-2541(98)00043-6, 1998.

IPCC: Global Warming of 1.5°C. An Intergovernmental Panel on Climate Change 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, https://doi.org/https://doi.org/10.1017/9781009157940, 2018.

IPCC: Summary for Policymakers: Synthesis Report., Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 1–34, 2023.

KrWG: Deutscher Bundestag: Kreislaufwirtschaftsgesetz vom 24. Februar 2012 (BGBl. I S. 212), das zuletzt durch Artikel 5 des Gesetzes vom 2. März 2023 (BGBl. 2023 I Nr. 56) geändert worden ist, https://www.gesetze-im-internet.de/krwg/KrWG.pdf, 2023.

KSpG: Deutscher Bundestag: Carbon Dioxide Storage Act of 17 August 2012 (BGBl. I p. 1726), which was latest modified by Article 22 on August 10th 2021 (Federal Law Gazette I p. 3436), https://www.gesetze-im-internet.de/kspg/inhalts_bersicht.html, 2012.

Kühn, M.: Chancen und Risiken: CO2-Speicherung, Chemie in Unserer Zeit, 45, 126–138, https://doi.org/10.1002/ciuz.201100538, 2011.

Li, Z., Fall, M., and Ghirian, A.: CCS risk assessment: Groundwater contamination caused by CO2, Geosciences (Switzerland), 8, https://doi.org/10.3390/geosciences8110397, 2018.

Lu, J., Partin, J. W., Hovorka, S. D., and Wong, C.: Potential risks to freshwater resources as a result of leakage from CO2 geological storage: a batch-reaction experiment, Environmental Earth Sciences, 60, 335–348, https://doi.org/10.1007/s12665-009-0382-0, 2010.

Lörch, D., Mohamed, A. G. A., Euchner, H., Timm, J., Bogdanoff, P., and May, M. M.: From CO 2 to solid carbon : reaction mechanism , active species , and conditioning the Ce-alloyed GaInSn catalyst, chemrxiv, pp. 1–35, https://doi.org/https://chemrxiv.org/engage/chemrxiv/article-details/66c7743120ac769e5f79ebb7, 2024.

Lübben, A. and Leven, C.: The Starzach site in Southern Germany: a site with naturally occurring CO2 emissions recovering from century-long gas mining as a natural analog for a leaking CCS reservoir, Environmental Earth Sciences, 77, https://doi.org/10.1007/s12665-018-7499-y, 2018.

Markus, T. and Schaller, R.: Land-Use Implications of Carbon Dioxide Removal: An Emerging Legal Issue?, International Yearbook of Soil Law and Policy, 2022, 107–121, https://doi.org/10.1007/978-3-031-40609-6_5, 2024.

Martin, R., De Melo, B., Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muentan, M., Schaaf, E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A., San-Miguel, J., and Vignati, E.: Greenhouse Gas Emissions of All World Countries, Publications Office of the European Union, https://doi.org/10.2760/235266, 2023.

May, M. M. and Rehfeld, K.: ESD Ideas: Photoelectrochemical carbon removal as negative emission technology, Earth System Dynamics, 10, 1–7, https://doi.org/10.5194/esd-10-1-2019, 2019.

McLaren, D.: A comparative global assessment of potential negative emissions technologies, Process Safety and Environmental Protection, 90, 489–500, https://doi.org/10.1016/j.psep.2012.10.005, 2012.

OGE - Open Grid Europe: CO2-Netz, https://oge.net/de/co2/co2-netz, [Accessed: 02-Oct-2024], 2024.

Reinhold, K. and Müller, C.: Speicherpotenziale im tieferen Untergrund-Übersicht und Ergebnisse zum Projekt Speicher-Kataster Deutschland, Schriftenreihe der Deutschen Gesellschaft für Geowissenschaften, pp. 9–27, 2011.

Smith, P.: Soil carbon sequestration and biochar as negative emission technologies, Global Change Biology, 22, 1315–1324, https://doi.org/10.1111/gcb.13178, 2016 b.

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., Van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W. K., Jonas, M., Jones, C. D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J. R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., and Yongsung, C.: Biophysical and economic limits to negative CO2 emissions, Nature Climate Change, 6, 42–50, https://doi.org/10.1038/nclimate2870, 2016 a.

Smith, S. M., Geden, O., Nemet, G., Gidden, M., Lamb, W. F., Powis, C., Bellamy, R., Callaghan, M., C., A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lück, S., Mohan, A., Müller-Hansen, F., Peters, G., Pratama, Y., Repke, T., Riahi, K., Schenuit, F., Steinhauser, J., Strefler, J., Valenzuela, J. M., and Minx, J. C.: The State of Carbon Dioxide Removal - 1st Edition, https://www.stateofcdr.org, 2023.

Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., and Vaughan, N. E. e.: The State of Carbon Dioxide Removal- 2nd Edition, The State of Carbon Dioxide Removal, 2024.

State Office for Mining, Energy and Geology - Germany: GeoReport 49: Natural gas and crude oil in Germany 2022, 2023.

Statistical Offices of the Federal Government and the Federal States: Environmental economic accounts of all federal states - Indicators and key figures, https://www.statistikportal.de/de/ugrdl, 2022.

Statistical Offices of the Federal States Germany: Environmental economic accounts of the federal states 2022 - Indicators and key figures, Statistical offices of the federal states, 2022.

Strefler, J., Amann, T., Bauer, N., Kriegler, E., and Hartmann, J.: Potential and costs of carbon dioxide removal by enhanced weathering of rocks, Environmental Research Letters, 13, https://doi.org/10.1088/1748-9326/aaa9c4, 2018.

Thengane, S. K. and Bandyopadhyay, S.: Biochar mines: Panacea to climate change and energy crisis?, Clean Technologies and Environmental Policy, 22, 5–10, https://doi.org/10.1007/s10098-019-01790-1, 2020.

Vilarrasa, V. and Rutqvist, J.: Thermal effects on geologic carbon storage, https://doi.org/10.1016/j.earscirev.2016.12.011, 2017.

Zoback, M. D. and Gorelick, S. M.: Earthquake triggering and large-scale geologic storage of carbon dioxide, Proceedings of the National Academy of Sciences of the United States of America, 109, 10 164–10 168, https://doi.org/10.1073/pnas.1202473109, 2012.

Zondervan, J., Hilton, R., Dellinger, M., Clubb, F., Roylands, T., and Ogrič, M.: Rock organic carbon oxidation CO2 release offsets silicate weathering sink, Nature, accepted, https://doi.org/10.1038/s41586-023-06581-9, 2023.