ASMASYS

# Unified ASsessment framework for proposed methods of MArine CDR and interim knowledge SYnthesiS (ASMASYS)

**AP3: Assessment of marine CDR-Methods and Interim-Synthesis**

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CDRmare
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# 1. Introduction

Governments worldwide, as signatories to the Paris Agreement COP21, have acknowledged the necessity of mitigating anthropogenic climate change by committing to limit the global average temperature increase to well below 2°C above pre-industrial levels and to strive towards limiting it to 1.5°C above pre-industrial levels (IPCC, 2018). The significant and rapid changes in the Earth's climate patterns caused by the climate crisis are primarily due to human activities, particularly the burning of fossil fuels, deforestation and industrial processes that release greenhouse gasses (GHG) into the atmosphere. These GHG, such as carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$), trap the sun's heat, leading to global warming and changes in weather patterns. Consequences of global warming are regionally rising temperatures leading to more frequent and intense heat waves, melting ice caps and glaciers, rising sea levels, extreme weather events, disruption of ecosystems and impacts on agriculture and food security, for example through crop failures. Thus, the urgency of mitigating climate change is crucial.

The Intergovernmental Panel on Climate Change Special Report on Global Warming (IPCC, 2018) emphasizes that all ways to limit warming to 1.5 °C require the use of carbon dioxide removal (CDR) technologies in addition to immediate emission reductions. Moreover, CDR would need to be deployed to a significant extent (100–1,000 Gt $CO_2$ over the course of the 21st century). Even in limiting warming to 2°C, virtually all pathways also require the use of CDR. Current scenarios, such as those outlined by the IPCC, have thus far exclusively focused on land-based CDR methods. However, achieving climate mitigation goals with land-based methods alone will be extremely challenging, if not impossible (Smith et al. 2015; Boysen et al. 2017). Knowledge about how the ocean could contribute to necessary net-zero strategies is limited, despite covering 70% of the Earth's surface and serving as the largest long-term sink for anthropogenic $CO_2$, illustrating the immense potential for CDR application in the marine realm. Additionally, enhanced ocean-based carbon sequestration measures complement those on land and include strategies that improve the ocean's natural physical, chemical, and biological processes for capturing $CO_2$ (Keller et al. 2018).

The research mission of the German Marine Research Alliance (DAM), CDRmare, consists of six consortia investigating different methods of marine $CO_2$ removal and storage applications and the extent to which the ocean can play a significant role in the removal and storage of $CO_2$ from the atmosphere. These methods are assessed for their potential, risks, and trade-offs within the transdisciplinary framework of ASMASYS. The potential, feasibility, and side effects of different methods of atmospheric $CO_2$ removal by ocean alkalinity enhancement (OAE) are being investigated by the RETAKE consortium. OAE reduces the partial pressure of $CO_2$ in seawater, enhancing the net flux of $CO_2$ from the atmosphere to the ocean and reducing the atmospheric $CO_2$ concentration. RETAKE examines various mineral alkalinity sources, analyzing their dissolution kinetics, $CO_2$ removal potential, and chemical and biological side effects. Efforts to increase the carbon storage capacity of various coastal ecosystems (blue carbon) by reversing the decline in their effectiveness as natural carbon sinks was investigated as part of the sea4soCiety consortium. The consortium analyzes habitat characteristics, such as vegetation biomass and organic material deposits in marine sediments in different coastal regions, to identify suitable areas for ecosystem expansion. Artificial ocean upwelling, aimed at enhancing primary productivity, is being investigated for its potential to sequester $CO_2$. Test-ArtUp is examining this method through a transdisciplinary approach, assessing technical application, environmental impacts, and governance requirements to provide recommendations for implementation and contribute to the United Nations Sustainable Development Goals.

With the amendment to the Climate Change Act, the federal government of Germany wants to reinforce climate regulation by making a legal commitment to reach net zero greenhouse gas emissions by 2045, with the aim of reducing emissions to 65 percent of 1990 levels by 2030. To achieve its emissions targets, Germany must reduce its emissions (about 746 Mt $CO_2$ equivalent in 2022) by 2045. Despite maximum efforts to avoid emissions, it is assumed that the remaining $CO_2$ emissions will continue into the middle of the 21st century, although there are uncertainties about their extent and the permissible sectors. Estimates suggest that Germany could face residual emissions of 32 to 60 million tons of $CO_2$ annually under optimistic emission avoidance scenarios (Borchers et al. 2024). Residual $CO_2$ emissions are currently unavoidable in cement and steel production, in transportation industries (air, shipment, heavy good vehicles), and in agriculture and waste incineration (Buck et al. 2023, Marmier 2023). Another innovative approach to reduce these emissions is marine carbon storage in the deep geological formations (e.g. sandstone formations below the North Sea, see GEOSTOR) or into basaltic deep-sea crust (see AIMS[3]) which involves the injection of land-derived $CO_2$ into porous rock beneath the seabed (Zhao et al. 2024). The seafloor, particularly sandstone and basaltic crust, offers significant $CO_2$ storage capacity, considered safer and more durable than conventional methods due to additional mineralization (Bachu, Gunter, and Perkins 1994; McGrail et al. 2017). This approach is exemplified by the Sleipner formation in the North Sea, where Statoil has operated since 1996, storing around 1 Mt/yr of $CO_2$. This method achieves cost-effectiveness of less than 50 €/t of $CO_2$ by repurposing depleted oil and gas reservoirs and utilizing existing infrastructure.

In addressing the urgent need for research into the ocean's capacity to store, absorb and sequester $CO_2$ from the atmosphere, it is imperative to underscore the importance of incorporating non-natural-science considerations across all marine carbon dioxide removal and storage technologies. This includes a robust focus on legal, social, and ethical dimensions, alongside careful attention to political frameworks and inherent policy mechanisms.

In ASMASYS, one of the main goals is to establish a comprehensive assessment framework for marine carbon dioxide removal (mCDR) and marine carbon storage (mCS) options, serving as a foundational tool for evaluating various methods uniformly. This is essential for several reasons: As the marine environment offers enormous potential for mCDR and mCS initiatives to remove and store significant amounts of $CO_2$ from the atmosphere, these methods also come with unique challenges and risks, particularly in terms of environmental impact and regulatory compliance. By creating a comprehensive assessment framework, policy makers, scientists and stakeholders can evaluate and assess the feasibility, effectiveness, environmental and ethical implications of marine mCDR/mCS methods. In addition, such an assessment framework provides a structured approach to decision-making and ensures that proposed initiatives are in line with environmental sustainability goals and societal values. A standardized assessment process promotes transparency, accountability and public trust in mCDR/mCS initiatives and facilitates informed dialogue and stakeholder engagement. Overall, the creation of an assessment framework is critical to the responsible development and implementation of mCDR and storage methods, balancing the potential benefits with the need to minimize environmental and social risks.

# 2. Current Regulatory Framework and Future Directions for mCS and mCDR in Germany

Currently sub-seabed carbon storage and most marine carbon removal approaches are restricted or prohibited under German law (KSpG, HSEG). However, this seems set to change, as let by the BMWK, the current government has indicated in the recently released 'cornerstones' for both a Carbon Management Strategy (CMS) and a Long Term Negative Emissions Strategy (Cabinet clears path for CCS in Germany (PR: 29/05/2024); Eckpunkte der Bundesregierung für eine Carbon Management-Strategie; Long-term Strategy for Negative Emissions (BMWK, 26/02/2024)).

Germany aims to become one of the first major climate-neutral industrial countries by 2045. To achieve this, the government has undertaken significant efforts over the past two years, including expanding renewable energy, decarbonizing industry, scaling up the hydrogen economy, promoting e-mobility, strengthening emission trading, accelerating planning and permitting processes, and advancing the heat transition in buildings (15/03/2024 – PRESS RELEASE – Climate Change Mitigation Germany on track for 2030 climate targets for the first time). The overarching goal is greenhouse gas emission avoidance, with decarbonization remaining central to climate protection. This involves phasing out coal and fossil fuels in general (Kohleausstiegsgesetz). Current scientific consensus and recent reports, including those from the IPCC, indicate that achieving climate neutrality by 2045 will necessitate the use of Carbon Capture and Storage/Utilization (CCS/CCU) technologies (Lee et al. 2023). This is because certain emissions are difficult or impossible to avoid through other means. These sectors face increasing cost pressures due to rising prices of European emissions trading certificates. The German government will establish the foundation for using CCS/CCU technologies, including $CO_2$ transport and storage, through a comprehensive Industrial Carbon Management (ICM) Strategy.

Following extensive dialogue with stakeholders from civil society, science, and industry, the government has outlined key points for this strategy, which will be further detailed in the near future. Internationally, CCS/CCU technologies are advancing rapidly. Several European countries, along with the USA, are developing geological storage projects. The European Commission is also promoting these technologies through the Net Zero Industry Act (NZIA) and the ICM Strategy. To align with the climate neutrality target by 2045, the current hurdles to the application of CCS/CCU in Germany will have to be removed. The government will promote the use of these technologies in line with the goals of the German Climate Protection Act (KSG).

The expansion of renewable energies will continue, supported by the construction of new gas-fired power plants that will transition to hydrogen. CCS/CCU applications in coal-fired power plants will not be allowed, and the use of $CO_2$ pipelines for coal emissions is excluded. State funding for CCS/CCU will focus on hard-to-avoid emissions. The Carbon Dioxide Storage Act (KSpG) will be updated to facilitate the construction of $CO_2$ pipelines under a regulated framework, removing legal uncertainties. Germany will ratify the amendment to the London Protocol to allow $CO_2$ exports for offshore storage and amend relevant national laws accordingly (Cabinet clears path for CCS in Germany (PR: 29/05/2024). Exploration of offshore storage sites in Germany’s exclusive economic zone (EEZ) and continental shelf will be legally enabled, with storage allowed upon proven site suitability, excluding marine protected areas. The permanent storage of $CO_2$ on German onshore territories remains prohibited unless individual federal states opt-in under specific legal provisions. The ICM Strategy will complement the Long-term Strategy for Negative Emissions (BMWK, 26/02/2024), focusing on unavoidable residual emissions and their offset through technologies like Direct Air Capture and Storage (DACCS) and Bioenergy with Carbon Capture and Storage (BECCS). The German Energy Agency (DENA) acknowledges the current legal impossibility of storing $CO_2$ domestically due to the KSpG and advocates for a national storage infrastructure, highlighting benefits such as shorter transport routes and lower costs.

To meet climate goals, DENA recommends allowing $CO_2$ exports to international storage sites in the short term and legal adjustments to support Carbon Capture and Utilization (CCU) for the chemical industry. They stress limiting CCS to unavoidable emissions and prioritizing emission reduction through renewable energy and efficiency improvements, proposing a cascade utilization approach in line with the National Circular Economy Strategy. These technologies require $CO_2$ infrastructure and storage, which the strategy will address. The National Biomass Strategy will also consider BECCS in light of limited sustainable biomass availability. The application of CCS/CCU will be part of a broader mix of instruments and technologies for decarbonization, particularly in the industry and waste management sectors. For process emissions, such as those from cement and lime production, CCS/CCU is essential for achieving climate neutrality. The technology will also be crucial for the waste treatment sector, where emissions are currently unavoidable. While the primary focus for power generation will remain on expanding renewable energy, CCS/CCU will be allowed for gas-fired power plants and biomass use. The government recognizes that the EU Emissions Trading System (EU ETS) already incentivizes CCS/CCU by allowing the accounting of captured $CO_2$. The latest EU ETS reforms also facilitate transport infrastructure development. However, additional state support will be required to cover the higher costs of climate-neutral production in industries like cement and lime. The strategy includes fostering a private pipeline infrastructure for $CO_2$ transport, crucial for integrating into the European carbon management framework. Germany will adjust its legal framework to support the development of this infrastructure, addressing current legal barriers. Offshore storage is prioritized due to its proven safety and the potential cost benefits of proximity to the German coast.

Overall, the German Federal Cabinet has approved the CMS to enable commercial-scale storage of non-avoidable $CO_2$ for industrial use, ensuring ecological criteria and high safety standards. This involved an update on the legal framework to support offshore storage exploration and development while excluding marine protected areas. The onshore storage will remain restricted, with potential opt-in provisions for federal states. The strategy ensures the responsible handling of $CO_2$ emissions, integrating storage solutions into comprehensive marine spatial planning and fostering collaboration within the European Union for carbon management and storage (Cabinet clears path for CCS in Germany (PR: 29/05/2024). In February 2024, the BMWK released another document outlining the cornerstones of its planned Long-term Strategy for Negative Emissions (BMWK, 26/02/2024), which includes references to marine and land-based CDR approaches. Building on the findings of the BMBF research programs CDRmare and CDRterra, the LNe will likely focus on key aspects such as: Societal perceptions to assess public acceptability of $CO_2$ removal in Germany, identifying opportunities and risks, and proposing effective solutions. Regulatory measures to examine regulations to unlock potential for negative emissions while ensuring all technologies adhere to the precautionary principle to avoid irresponsible risks:

- Research and Development to continue foundational and applied research, including field experiments to transition lab findings to field tests to gather practical knowledge.
- Expansion of the High Sea Dumping Act (HSEG) to extend exemptions to include ocean alkalinity enhancement and $CO_2$ mineralization in the ocean crust.
- Integration with Existing Policies to ensure alignment with the CMS and natural climate protection methods.
- Comprehensive evaluation to develop methodologies for life-cycle assessments to evaluate various approaches, including their co-benefits and trade-offs.
- Interdisciplinary research to address cross-disciplinary questions related to public acceptability to investigate societal attitudes and appropriate incentive frameworks. Regulatory and political frameworks to understand interactions with other sustainability goals.
- Monitoring, Reporting, and Verification (MRV) to enhance methods for accurate tracking and assessment.

It must be taken into consideration that this document is preliminary, and it will be a long dialog and political process before the final strategy is developed and adopted. In sum, the regulatory landscape for mCS and mCDR in Germany is currently changing and seems set to become more permissive in the future.

# 3. Public Perceptions of mCDR/mCS Technologies

Public acceptability is considered one of the most significant constraints on the deployment of CDR technologies (Fuss et al. 2014; Rogelj et al. 2018; Rickels et al. 2019). An expert survey of earth system modelers and integrated assessment modelers viewed political and public acceptability as the primary limitation on the feasibility of ocean iron fertilization, alkalinity enhancement, and artificial upwelling, with cost effectiveness being the next major concern. Conversely, they regarded public acceptability as a minor constraint for blue carbon management (Rickels et al. 2019). There have been recurring public and environmental protests against mCDR research projects on iron fertilization such as LOHAFEX in the Southern Ocean (Schiermeier 2009) or the Haida Salmon Restoration Corporation in international waters off the Canadian west coast (Gannon and Hulme 2018), projects involving $CO_2$ injection into the deep sea off Hawaii and Norway (de Figueiredo, Reiner, and Herzog 2003) or, most recently, protests against an ocean alkalinization start-up in Cornwall (The Guardian 2024). These instances highlight significant societal opposition to future exploration and deployment of some mCDR/mCS methods. Early research has primarily focused on public perceptions of ocean fertilization and direct $CO_2$ injection (Bertram and Merk 2020), only recently studies on newer proposals like artificial upwelling, biomass dumping, or Ocean Alkalinity Enhancement (OAE) have been done (Nawaz et al. 2023; Andersen, Merk, and Tvinnereim 2023).

Compared to abatement technologies such as renewable energy and energy efficiency, ocean fertilization and $CO_2$ injection have been negatively evaluated (Palmgren et al. 2004). Perceptions of technologies like carbon capture and storage (CCS), and land-based CDR is influenced by perceptions of attributes like naturalness, controllability, storage duration, environmental impacts, and risks (Palmgren et al. 2004; Amelung and Funke 2015; Bertram and Merk 2020; Cox et al. 2020; Lueck et al. 2024). Resistance from local communities can severely limit the deployability of mCDR (Myatt, Scrimshaw, and Lester 2003; West 2010; Gannon and Hulme 2018; Bertram and Merk 2020). Research gaps exist, particularly in understanding the relationship between local and global effects of mCDR, given uncertainties around its impacts on local populations and ecosystems, as well as potential transregional or global interactions.

# 4. Project ASMASYS

## 4.1 Scientific Objectives and Relation to the Funding Policy

The main objective of the project ASMASYS (Unified ASsessment framework for proposed methods of MArine CDR and interim knowledge SYnthesiS) is to assess the currently proposed marine methods for carbon dioxide removal (mCDR) and carbon storage (mCS) using a standardized, transdisciplinary assessment framework. This includes in detail:

- Conducting the fundamental transdisciplinary research necessary to develop an integrative assessment framework for mCDR options, in close exchange with the activities of the CDR funding line;
- An interdisciplinary assessment of individual mCDR options, including methods investigated within the other funded consortia of the mission, as well as other less investigated mCDR options considered within ASMASYS based on literature and exchange with experts;
- Provide transdisciplinary scientific input for tailored stakeholder feedback, with a particular focus on German national mCDR interests and strategies.
- Develop comprehensive feasibility and desirability dimensions within the framework as tools for assessing mCDR and mCS options.

## 4.2 The ASMASYS Assessment Framework

The assessment framework comprises a structured set of criteria and underlying indicators, organized into seven assessment dimensions. These dimensions inform two overarching assessment questions: one addressing the **'Feasibility'** (what can we do?) of the assessed mCDR options and the other addressing their **'Desirability'** (what should we do?/what would be good or bad to do?). Its objective is to assist users in determining which mCDR options are implementable and which should be prioritized. Current assessment frameworks often focus on specific areas like biodiversity impacts, lack clarity on their assessment goals, or primarily assess feasibility, only implicitly considering other factors such as equity. While equity considerations are important, they may not always directly influence feasibility. In a world marked by structural inequalities, policies that meet fairness criteria may not necessarily be the most feasible. By gathering crucial questions pertaining to feasibility *and* desirability, the framework offers proposed criteria and indicators for evaluation. A detailed description will be given in Baatz et al. (to be submitted).

## 4.3 The Seven Dimensions of the Assessment Framework

The assessment of mCDR options encompasses three feasibility dimensions and four desirability dimensions. We imply no judgment on importance for each of the dimensions. Each dimension includes three to five criteria used to evaluate the performance of an mCDR option. Each criterion is associated with several indicators that assess whether the criteria are met and to what extent. These indicators, whether quantitative or qualitative, form the empirical basis of the assessment process:

**Techno-environmental Feasibility** addresses the fundamental question of whether there are both the technical means and environmental conditions necessary to implement a particular mCDR option, asking the key question: Is suitable Infrastructure and technology available? Does the environment allow the option?

**Political Feasibility** is about whether a particular mCDR option can find sufficient support in democratic systems or at least avoid significant opposition from elected representatives and the public (Is the option politically possible?). Factors such as political contestation, consistency with existing climate policies and the existence of policy instruments that ensure transparency and accountability influence the political feasibility of mCDR initiatives.

**Legal Feasibility** assesses whether the implementation of a mCDR option complies with current regulatory requirements (Is the option legally allowed?), taking an abstract approach to account for future regulatory changes. It focuses on five key areas typically found in hazardous activities regulations and ensures adaptability over time and across different levels of legislation, including international, regional and national.

The **Effectiveness** dimension assesses the potential positive climate impacts of mCDR options (How effective in reducing climate change is the option?), ensuring that selected methods contribute significantly to achieving climate mitigation goals. While some criteria such as CDR potential and permanence are intuitive and widely used, others such as quantification and verification, indirect climate- and termination effects are less researched and may be defined differently in different assessment frameworks.

**Economic Efficiency** in the evaluation of mCDR options encompasses more than just financial costs; it considers the allocation of resources to maximize societal welfare. An option is considered desirable if it minimizes the cost per unit of CDR, reflecting its efficiency. Therefore, economic efficiency is a key factor in assessing the desirability of mCDR options considering the question: What are the costs and benefits of the option?

The **Justice** dimension includes distributive justice, which asks whether benefits and burdens are fairly distributed, and procedural justice, which emphasizes the need for fair decision-making processes (How fair is the governance and the distribution of benefits and burdens among humans?). Within the Justice dimension, impacts on the natural world are only considered insofar as they affect humans, while the environmental ethics dimension enables users to assess wider impacts on the natural world.

The **Environmental Ethics** dimension recognizes that effects on the natural world are important beyond their impact on humans. It allows users of the framework an assessment of mCDR options that is not only centered on human needs, but makes room for the insight that effects on animals, biodiversity, and ecosystems matter in and of themselves.

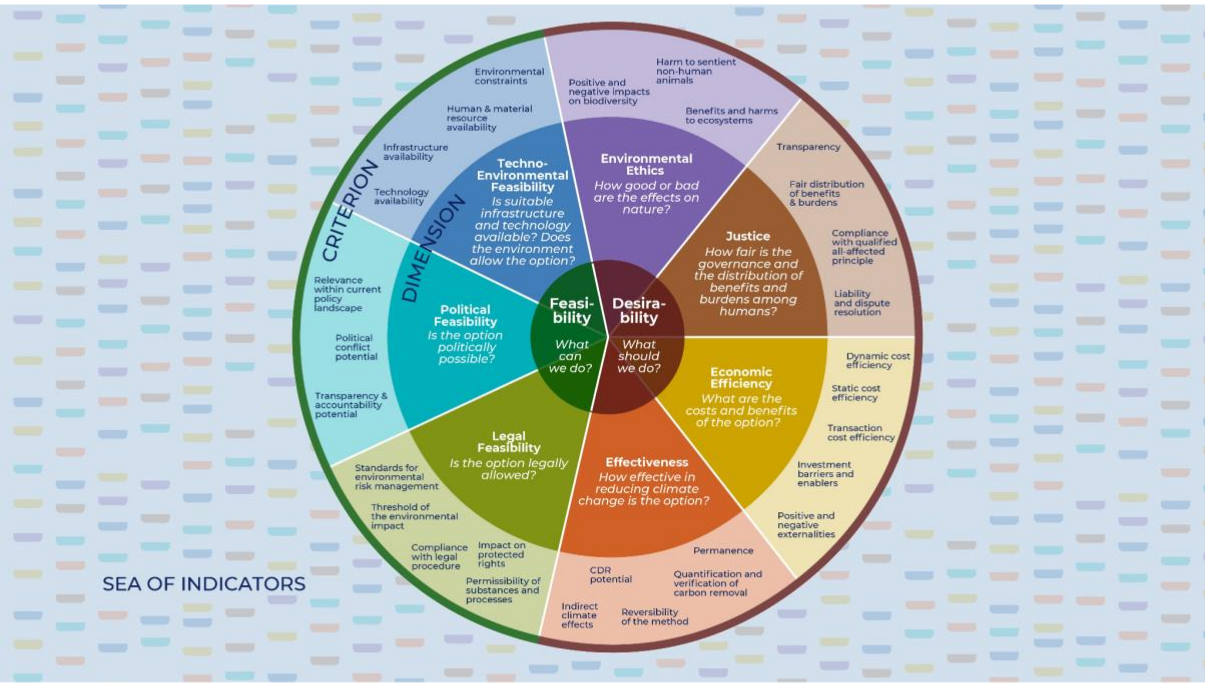

Figure 1: The ASMASYS assessment framework for mCDR options. The central overarching questions Feasibility: What can we do? and Desirability: What should we do? are surrounded by the seven dimensions (all of which are equally important) and the criteria, each relating to a set of indicators (Sea Of Indicators), which can be quantitative or qualitative and serve as the empirical foundation on which the assessment process rests (Baatz et al, to be submitted).

## 4.4 Proof of Concept with Hypothetical Test Cases

The aim of hypothetical test case scenarios was to facilitate a structured, open discussion using hypothetical scenarios within the ASMASYS assessment framework to assess its effectiveness in addressing essential questions for informed decision-making. The test cases were designed to be plausible but entirely hypothetical, allowing for initial assessment of specific CDR methods. To evaluate each dimension, we developed a questionnaire containing 10 to 18 questions based on relevant indicators for each dimension. Each question was thoroughly discussed at *Think and Exchange Tank* meetings, responses were recorded, and an overall verdict was reached for each dimension based on these discussions. The creation of the test cases were designed to be scientifically robust and as realistic as possible within the framework of the exercise and provided valuable reviews considering whether the assessment framework addresses the key questions needed to be answered in order to make an informed decision. Each of the four scenarios offered distinct insights into the dimensions of different mCDR approaches. The following four distinct methods were evaluated using the test cases:

**Test Case 1: Ocean Alkalinity Enhancement (OAE)**

14th TET, 3 - 4th July 2023 (Berlin): Small scale, coastal OAE experiment. Stakeholders attended from: German Environment Agency (UBA), Federal Agency for Nature Conservation (BfN), Bundesamt für Seeschifffahrt und Hydrographie (BSH), World Wide Fund for Nature (WWF)

**Test Case 2: Blue Carbon Ecosystem (BCEe) Enhancement**

16th TET, 25 - 26th September 2023 / (Warnemuende): Designing kelp forest ecosystems in the coastal waters of Sylt as a carbon removal measure.

Stakeholders attended from: German Environment Agency (UBA), Federal Agency for Nature Conservation (BfN)

**Test Case 3: Marine carbon storage (mCS) in deep-sea crust**

17th TET, 6 - 7th February 2024 / (Berlin): Marine carbon dioxide storage in deep- sea basaltic rock off Norway. Stakeholders attended from German Environment Agency (UBA), Bundesamt für Seeschifffahrt und Hydrographie (BSH), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)

**Test Case 4: mCS in sandstone formations in the North Sea**

19th TET, 23th of May 2024 (online): Project GEOSTOR (No stakeholder involved, because a stakeholder event had been hosted by GEOSTOR briefly before, and feedback was considered during the assessment of the test case)

By addressing specific elements such as techno-environmental feasibility, political dynamics, legal complexities, and ethical considerations, a holistic understanding of these approaches was achieved. By using the indicators (see supplement page 33) each test case contributed to a more holistic understanding of these approaches and identified and pushed the boundaries of mCDR/mCS technologies, highlighting limits, challenges and opportunities in their implementation. However, some scenarios lack detailed information, hindering a comprehensive assessment, yet they reflect a realistic situation, highlighting the need for further research and method development for realistic scenarios. For instance, in a hypothetical test case, the primary gap arises from its theoretical nature, which lacks real-world complexities. In general, there is a need for more explicit consideration of legal and ethical dimensions, as well as the entire value chain of mCDR and mCS processes. Major gaps for most real-world mCDR and mCS applications include climate relevant upscaling, cost estimations, administrative responsibilities, planning, and monitoring, reporting, and verification (MRV) mechanisms. Localized solutions are crucial, emphasizing the need to tailor approaches to specific contexts, even for small scale applications.

## 4.5 The 10 Mt $CO_2$ $yr^{-1}$ Removal Challenge for Germany

The "10Mt $CO_2$ $yr^{-1}$ Removal Challenge for Germany" (Yao et al. 2024, submitted) has been integrated into the Project ASMASYS to evaluate the feasibility and potential of marine carbon dioxide removal (mCDR) and geological carbon storage (mCS) technologies within the specific context of Germany. This initiative aims to address the urgent need for effective climate change mitigation strategies by exploring the capacity of mCDR and mCS to contribute significantly to Germany's net-zero targets.

The challenge focused on identifying options capable of removing 10 million tonnes (Mt) of $CO_2$ annually, which represents 8-22% of Germany's projected hard-to-abate and residual emissions by 2045. By concentrating on site-specific conditions, such as local resource availability, geophysical constraints, infrastructure, and jurisdictional considerations, the approach aimed to provide a realistic assessment of the implementable potential of these technologies.

Like the four cases mentioned above, we generated ten different mCDR and MCS options based on the expertise of four methodologies present within CDRmare (alkalinity enhancement, blue carbon, artificial upwelling, and geological storage) by varying the deployment locations and/or exact components within the operation chain. We evaluated ten different mCDR and mCS options, examining their environmental, resource, and infrastructure requirements. Among these, we have identified six options with the potential to meet the 10 Mt $CO_2$ removal target. Notably, three options appear feasible within German jurisdiction: the electrolytic production and addition of alkalinity-enhanced solution from silicate rock, the production and dispersal of $Ca(OH)_2$ along ship tracks in the North Sea, and the use of biomass from macroalgae farming for biomethane production combined with carbon storage in saline aquifers in the North Sea.

By integrating the "10Mt Challenge" into ASMASYS, we aimed to provide a comprehensive basis for further research and policy development. This integration helps highlighting the main uncertainties and bottlenecks, ranging from geophysical constraints and material availability to technological readiness and infrastructure capacity. Additionally, it underscores the importance of considering mCDR and mCS as crucial components in Germany's portfolio of climate mitigation strategies.

Ultimately, this initiative seeked to ground the expectations for large-scale CDR implementation in realistic assessments, ensuring that optimistic projections do not undermine immediate emissions reduction efforts.

# 5. Operational Capability and Capacity of the Dimensions of the Assessment Framework

The **Techno-Environmental Feasibility** of mCDR initiatives presents opportunities and challenges. One crucial starting point for the exploration of mCDR and mCS options is the presence of favorable environmental conditions and the Technological Readiness Levels (Terrile et al. 2015), which establish a solid foundation for advancing these initiatives. However, while these conditions offer promise, scalability emerges as a critical consideration. Many mCDR technologies are still in the early stages of development or testing (Eisaman et al. 2023). Scaling up these technologies requires advancing Technology Readiness Levels (TRLs) where they are proven to work reliably at larger scales. This requires substantial infrastructure, such as specialized vessels, equipment, facilities, or significant amounts of resources, including materials and green energy which may not be readily available or cost-effective at smaller scales.

Success in implementing large-scale mCDR initiatives hinges on the ability to navigate integration challenges and adapt technologies to specific environmental contexts. Despite the theoretical feasibility of some mCDR and mCS solutions, discussions of practical implementation scenarios revealed complexities and gaps that need addressing. Further uncertainties persist, particularly in predicting long-term suitability and effectiveness in the face of environmental changes, including the impacts of climate change. Insufficient environmental mapping and limited involvement from the private sector further impede progress in this area. Large-scale deployment of mCDR methods could have unforeseen environmental impacts, such as altering marine ecosystems or affecting ocean chemistry. Understanding and mitigating these impacts is essential for scalability. Moving forward, overcoming these challenges requires concerted efforts. Clear communication, collaboration, and transparency among stakeholders and society are essential for success. Additionally, mapping relevant actors and fostering cooperation will be vital steps in advancing Techno-Environmental Feasibility. Addressing integration obstacles and navigating uncertainties in the environment are crucial for realizing the potential of large-scale mCDR initiatives to reduce atmospheric $CO_2$ concentrations and contribute to climate change mitigation, while at the same time protecting and restoring the environment.

**Political Feasibility** is shaped by the combined motivation and capacity of a set of political actors to achieve a specific outcome (Jewell and Cherp 2020), e.g. research, development, demonstration or deployment of marine CDR and/or mCS options. (Patterson et al. 2018). Though public perceptions and media portrayals of the proposed options certainly constitute important factors, the rationalities of political organizations responsible for setting collectively binding rules and regulations - parliaments and public administrations - often play a key role in determining the political feasibility of these options. The positions of these types of political organizations - and the level of conflict between them - is key to determining the political feasibility of mCDR & mCS activities (Geden 2016; Boettcher, Schenuit, and Geden 2023). The extent to which mCDR fits within the existing climate policy landscape of a given country or region will also affect its political feasibility. And lastly, whether there are policy instruments in place to ensure the transparency and (political) accountability of a given mCDR implementation will play a large role in feasibility. Political feasibility further hinges on electoral outcomes, international developments, and the transparency of the mCDR debate, with the media playing a crucial role in shaping narratives and transparency. Key insights include the necessity for broad political support to drive mCDR initiatives and the acknowledgment of NGOs' political agendas.

The debate around the social acceptability of mCDR is shaped by past experiences with the protest around research projects (Bertram and Merk 2020; Otto et al. 2022). These conflicts showed that it is important to engage early on with affected publics and to communicate transparently to consider their concerns in decisions about and design of mCS and mCDR) projects. An open and comprehensive political debate is necessary but, especially if it becomes polarized, the political promise offered by mCS and mCDR could also lead to further delays in immediate decarbonisation efforts (Boettcher et al. 2021; Low and Boettcher 2020). The possibility of continued use of fossil fuels, together with the financial implications, could affect the likelihood of these measures being accepted and implemented by policy makers and stakeholders. Knowledge gaps include economic feasibility, the role of media, and how mCDR may be integrated into marine spatial planning. The level of public awareness and perception regarding offshore mCDR/mCS also requires further exploration.

**Legal Feasibility** is shaped by both domestic barriers and international uncertainty. While potential feasibility in Germany by 2028 is contingent on foreseeable legal changes (Borchers et al. 2024), deployment beyond national waters depends on international regulations which are slower to evolve. Unfortunately, there is currently a high degree of legal uncertainty at the international level due in part to the lack of scientific data concerning adverse impacts and the absence of political consensus on every aspect of the matter. This makes mCDR in international waters legally risky, which may discourage economic actors. However, it is important to recognize that legislation can be enabling, and good international legislation is a fundamental requirement for the success of mCDR. The London Protocol serves as a good example, providing an innovative approach to mCDR research that considers environmental risks while aiming to develop the knowledge base by providing a safe space to act. Political, economic, and legal considerations intersect, underscoring the importance of comprehensive approaches to assessing and planning mCDR implementation proposals.

The **Effectiveness** of marine carbon dioxide removal and storage initiatives is of utmost importance in mitigating climate change. Accurately monitoring and verifying net removal and long-term $CO_2$ storage is a major challenge. Monitoring long-term storage presents significant obstacles and requires innovative approaches to verification. Despite these challenges, experiments could offer valuable insights for scaling up mCDR efforts. A critical aspect of evaluating effectiveness is conducting a full life cycle assessment (LCA) to fully understand the overall effectiveness of removal. However, the importance of LCA goes beyond permitting to include effectiveness classification and scalability considerations.

There are still considerable uncertainties regarding the scalability of mCDR experiments and the extent of the compensation costs. In addition, understanding the economic feasibility and potential profitability of mCDR initiatives remains essential for decision-making. Transparent and international accounting systems are crucial for effective monitoring and review of mCDR initiatives. Ultimately, the effectiveness of mCDR and mCS efforts will shape future climate change mitigation strategies, underscoring the importance of robust experimentation and comprehensive assessments.

**Economic Efficiency** plays a pivotal role in scaling up marine carbon dioxide removal (mCDR) and storage (mCS) initiatives, transitioning from minor relevance in pilot studies to critical significance in larger-scale applications. The costs for technology development, Monitoring, Reporting, and Verification (MRV), and compensatory payments could substantially influence the cost efficiency of mCDR interventions. However, these costs remain unknown as to whether they accrue at all and to how high they would be. Precise estimation of starting costs is essential for realistic financial projections, yet challenges persist due to numerous unknowns regarding the effectiveness of the approach.

Additionally, the emphasis on cost reduction underscores the importance of clearly defining the economic benefits and profitability criteria associated with mCDR options.

Addressing these economic challenges requires transparent and international accounting systems to ensure effective cost management and financial planning. Stakeholders must have access to comprehensive information both before and after project implementation to facilitate informed decision-making. In summary, economic efficiency considerations become increasingly critical as mCDR and mCS efforts scale up, highlighting the need for precise cost estimation, clarity on cost allocation, and transparency in financial planning processes.

**Justice** considerations in marine mCDR strategies are multifaceted, with distributive justice often centering on the potential impacts on local communities and industries, including aspects such as tourism, fisheries, and cultural services. But distributive justice also is concerned with how burdens and benefits are distributed globally and intergenerationally. Procedural justice is also crucial, demanding meaningful inclusion in decision-making processes to ensure fair and equitable outcomes. There are significant gaps in current assessment standards, particularly concerning the environmental effects of mCDR technologies. The absence of permitting and comprehensive assessment processes for many mCDR technologies complicates the determination of distributive and procedural justice implications. Additionally, reconciling the heterogeneous fields of procedural and distributive justice presents a challenge, requiring integration to reach a unified verdict on justice.

Governance frameworks for addressing justice considerations remain uncertain, further exacerbating the complexity of the issue. Addressing justice considerations in mCDR strategies necessitates comprehensive assessment standards that encompass the entire value chain, including energy production and other land-based components such as space requirement. Balancing distributive and procedural justice requires meaningful inclusion in decision-making processes and careful consideration of the diverse impacts on local communities and ecosystems. Focusing on social justice could enhance the political feasibility of achieving 1.5°C or 2.0°C climate targets by legitimizing and inspiring both public and private actions on a scale that matches the urgent need for transformation (Patterson et al. 2018), which would contribute to intergenerational justice. Transparency, accountability, and access to environmental services must be prioritized in governance frameworks to ensure equitable outcomes for all stakeholders involved in mCDR initiatives. Ultimately, justice considerations must be integrated with effectiveness and economic efficiency assessments to comprehensively evaluate the impacts of mCDR strategies on humans and the environment.

**Environmental Ethics** considerations in mCDR strategies underscore the importance of comprehensive assessment standards of environmental effects. The size and scale of environmental effects play a significant role, with very localized impacts less likely to weigh heavily against an option. However, the ethical implications of replacing one ecosystem with another require careful study, particularly regarding the monitoring of connected areas. Current assessment standards for environmental effects lack comprehensiveness, highlighting a need for clearer guidelines that encompass the full spectrum of impacts. There is also uncertainty surrounding the weighting of verdicts on environmental ethics, with differing perspectives on the value of collective versus individual components of ecosystems. Additionally, the practical application of ethical principles varies, with some stakeholders advocating for direct accounting of impacts on plants and non-sentient life forms. Addressing environmental ethics in mCDR strategies necessitates a holistic approach that considers the broader ecosystem impacts and evaluates the trade-offs between different environmental values. Transparency and access to environmental information are crucial for ethical decision-making, emphasizing the need for clear guidelines and accountability mechanisms. Understanding the relationship between global and local benefits and the ethical implications of valuing carbon storage is essential for informed decision-making. Overall, environmental impacts should be central considerations in the development and implementation of mCDR strategies, with a focus on promoting sustainability and ethical stewardship of marine ecosystems.

# 6. Exploring Marine Carbon Dioxide Removal in Germany

The next chapter provides short overviews of two mCDR methods, offering insights into their status, estimated potential and public debate. Additionally, it includes a concise summary of the assessment based on the ASMASYS framework, evaluating each method's feasibility and desirability. The ASMASYS framework was refined through validation with stakeholders using hypothetical test cases (Chp. 4.4). designed to test the framework itself with mCDR technology-specific insights.

## 6.1 Ocean Alkalinity Enhancement

### Methodology, Potential and Technology Readiness Level

Ocean Alkalinity Enhancement (OAE) is a proposed method for marine carbon dioxide removal (mCDR) involving the introduction of $CO_2$-reactive alkaline minerals, chemical bases, or their dissociation products into ocean surface waters. This increases surface ocean alkalinity, reducing $CO_2$ partial pressure and potentially intensifying $CO_2$ uptake from the atmosphere or reducing $CO_2$ release from the ocean. Additionally, OAE has the potential to locally reduce ocean acidification by elevating pH levels and the theoretical durability of carbon storage (Hartmann et al. 2023). OAE shows significant sequestration potential, estimated at 3 to 30 Gt $CO_2$ $yr^{-1}$ (Köhler et al. 2013; Renforth and Henderson 2017; Feng et al. 2017), with multiple suggested deployment approaches (Oschlies et al. 2023).

By the urgent need to understand its carbon storage potential and associated risks, the Guide to Best Practices in Ocean Alkalinity Enhancement Research has been developed. This guide promotes responsible and transparent scientific research to rapidly generate reliable information and recommendations for effective experimentation and collaboration on OAE as a carbon dioxide removal strategy (Riebesell et al. 2023; Cyronak, Albright, and Bach 2023).

OAE is currently positioned in the "concept stage" cluster of ocean-based climate action measures, with high effectiveness potential but yet to be demonstrated regarding feasibility, environmental impacts and cost-effectiveness (Gattuso et al. 2021). So far only a few field experimental studies (<10) have started to address these challenges. Crucial knowledge gaps remain regarding alkalinity delivery and addition methods, alkalinity loss and stability, material processing and transport, ideal deployment locations, mCDR potential, durability of carbon storage, and socio-economic aspects (Hartmann et al. 2023; Bach 2024; He and Tyka 2023; Suitner et al. 2023). Several OAE methods have been developed, including injecting alkaline liquid into the ocean, dispersing alkaline particles from ships or platforms, adding minerals to coastal environments, and electrochemically removing acid from seawater. These OAE methods are at different TRLs (Eisaman et al. 2023) but relatively low: generally rated as 1-2 by (Lamb et al. 2023), 3-4 for specific methods (Foteinis et al. 2022; Foteinis, Campbell, and Renforth 2023), and possibly 5-6 for those with initial field trials in preparation or underway (Eisaman et al. 2023). For example, pilot studies for accelerated weathering of limestone (AWL) systems in Taiwan indicate TRL 5-6 and $CO_2$ Electrolysis with Water (CEW) is at TRL 4-5 undergoing field trials. Ocean Liming (OL) has also progressed to TRL 4-5. In Germany, the potential of enhanced benthic weathering in the Baltic Sea is explored by investigating weathering processes under anoxic to hypoxic conditions in corrosive bottom waters, revealing that added dunite and calcite significantly increase alkalinity release compared to control experiments (Fuhr et al. 2024). Each method has its own benefits and challenges related to scalability, cost-effectiveness, efficiency and potential environmental impacts.

The selection of a method depends on factors such as regional oceanographic conditions, availability of alkalinity sources, and engineering feasibility. Further research and development are essential to advance TRLs and evaluate the effects of these OAE methods under diverse oceanic conditions, addressing uncertainties in long-term ecological impacts and large-scale feasibility for mCDR. Scaling OAE to climatically relevant scales requires addressing technological, acceptability, and governance challenges, with robust MRV procedures and expanded climate policies needed for large-scale implementation (Ho et al. 2023; Nawaz et al. 2023). Despite these challenges, resolving these issues is crucial for realizing the potential of OAE in mitigating climate change.

Biggest challenges arise from the necessity and uncertainties for monitoring, reporting, and verifying (MRV) carbon sequestration rates, which are crucial for assessing $CO_2$ removal. An important aspect integrated into MRV for OAE is understanding ecosystem responses' impact on $CO_2$ removal. Recent research by (Bach 2024) highlighted the "additionality problem" of OAE. By artificially increasing the carbonate saturation state, OAE interventions can reduce natural sediment alkalinity release into surface ocean waters, decreasing estimated natural $CO_2$ removal by about 12%. Incorporating such biogeochemical feedbacks into MRV frameworks is crucial for accurately estimating OA intervention effectiveness in removing $CO_2$ and mitigating ocean acidification. This ensures adjustments to $CO_2$ removal estimates for more reliable and transparent assessments of OAE interventions' impact on mCDR.

## Public Debate and Perceptions

Research on public perceptions of ocean alkalinity enhancement (OAE) as a mCDR strategy is limited. Surveys by Nawaz et al. (Nawaz, Peterson St-Laurent, and Satterfield 2023) and (Merk, Andersen, and Tvinnereim 2023) found that respondents were least comfortable with OAE among the surveyed Negative Emission Technologies (NETs). This method elicited lower comfort levels compared to other NETs, including terrestrial options like soil sequestration and afforestation, as well as ocean-based methods like ocean fertilization. This indicates a public skepticism and discomfort towards ocean alkalinity enhancement as a marine carbon dioxide removal strategy. The concerns mirror those associated with enhanced weathering on land, particularly regarding perceived environmental impact risks on marine ecosystems and the extensive mining, transport and dumping of the materials required (Cox et al. 2020). In addition, a perceived lack of controllability drives negative associations (Merk et al. 2023).

These findings suggest that the preservation of the marine environment is a significant concern for the public, and there is little evidence to support the idea that ocean-based methods are perceived more favorably simply because they are out of sight. Ocean Alkalinity Enhancement is a critical component in achieving deep decarbonization of industry, aligning with broader efforts for carbon management and negative emission technologies (LibMod Policy Paper). Achieving widespread societal acceptance of these transformation processes requires complementary strategies. Changes in ocean alkalinity can impact regions differently. Engaging local communities and stakeholders early is crucial to understand their specific needs and challenges related to OAE implementation. Effective communication of OAE goals and impacts is vital. Information should be tailored to different audiences, using participatory and creative formats to foster knowledge transfer and dialogue among industry, policymakers, and the public. Building trust with citizens is essential. They should feel included and empowered to contribute to the OAE process. Addressing concerns openly is crucial for establishing trust. Honest and transparent discussions about the costs, benefits, and challenges of OAE are necessary. Openly discussing the possibilities and obstacles of ocean alkalinity enhancement supports informed decision-making and societal acceptance (Satterfield et al. 2023).

### Assessment by Dimensions

The review of OAE implementation through the ASMASYS assessment framework has highlighted both the significant potential and considerable challenges and uncertainties of this mCDR technology. At the 14th TET, (3 - 4th July, 2023 Berlin, Test-case 1) a hypothetical, small-scale, coastal OAE experiment planned for the German EEZ in the Baltic Sea starting in 2026 was discussed. This scenario involves introducing 10,000 tons of ground limestone at once to monitor its effects over a two-year period, aiming to gather crucial insights into the feasibility and desirability of OAE. The technological-environmental feasibility means favorable conditions with available infrastructure and suitable local conditions for experiments. In political terms, feasibility is a given, but depends on election results and EU-policy developments, whereby transparency is of crucial importance. Legally, there are still uncertainties, but legitimate OAE research could be allowed if the German relevant legislation (primarily the High Seas Dumping Act) is adapted as recently proposed by the BMWK (BMWK - Eckpunktepapier LNe), taking into account public participation and legal interventions (see also Chapter 2). Economically, the relevance for pilot studies is low, with overall positive assessments due to low costs, although the amount of costs for monitoring remains uncertain.

While the effectiveness of the test case is designed to be small, there is a potential gain in the ground knowledge of the method's "real world" effectiveness and its scalability (in the region). However, considerations of equity remain unclear, highlighting the need for specific evaluation questions. Pilot projects have demonstrated feasibility, but scaling up globally requires addressing logistical, regulatory, and funding obstacles and ensuring site selection tailored to regional variations for maximum efficiency. Implementation of best practices, including comprehensive environmental assessments and transparent public engagement, is crucial for responsible deployment and refining methodologies based on past experiences. Following best practices, as proposed in the Guide to Best Practices in Ocean Alkalinity Enhancement Research, is crucial.

## 6.2 Blue Carbon Ecosystem Enhancement

### Methodology, Potential and Technology Readiness Level

Blue Carbon Ecosystems (BCEs) or Blue Carbon (BC) refers to $CO_2$ that is absorbed from the atmosphere and stored as carbon in marine ecosystems. This includes carbon stored in underwater sediments, coastal vegetation and soils, as well as marine life. Blue carbon qualifies as a mCDR approach only when existing ecosystems are expanded. Simply restoring existing ecosystems counts only as emissions reduction (Mengis, Paul, and Fernández-Méndez 2023). However, it is important to state that the expected positive side effects are large and that restoration is framed by EU and German law, and will be implemented even if uncertainties concerning mCDR remain (EU Nature Restoration Law).

Mangroves, seagrass meadows, and tidal marshes, globally store over 30,000 teragrams of carbon (Tg C) across 185 million hectares and provide benefits like coastal protection and enhanced biological diversity and fisheries.

The amount of carbon dioxide ($CO_2$) emissions reduced, sequestered, or avoided by blue carbon ecosystems is expressed as $CO_2$ equivalents ($CO_2e$) allowing for the comparison and aggregation of different greenhouse gasses' impacts based on their global warming potential. Conserving these ecosystems could prevent 304 Tg $CO_2e$ annually (Macreadie et al. 2021). Restoration potential includes 0.2–3.2 million hectares of tidal marshes, 8.3–25.4 million hectares of seagrasses, and 9–13 million hectares of mangroves, which could sequester an additional 841 Tg $CO_2e$ per year by 2030, about 3% of global emissions based on 2019-2020 data (Macreadie et al. 2021).

Mangrove protection and restoration offer the highest carbon benefits (Jakovac et al. 2020), though more research is needed on both mangroves due to variability of carbon storage across locations and on other blue carbon ecosystems (BCEs) for various uncertainties. While stopping all BCE destruction is unlikely and not all losses can be restored, coastal protection planning offers restoration opportunities by valuing co-benefits. Prioritizing BCEs is a cost-effective and scalable climate solution, but barriers remain before blue carbon projects can be widely adopted. In terms of technological readiness, methods for restoring mangroves and salt marshes are well-developed and increasingly cost-effective. Seagrass bed restoration is more expensive and sometimes ineffective, with uncertain carbon storage benefits (Merk et al. 2022). Overall, blue carbon methods vary in their technological readiness (Merk, Grunau, et al. 2022). Mangroves and salt marshes are the most advanced and cost-effective, while seagrass and marine animal population methods are still developing and face more uncertainties. Despite these challenges, the ecological and social benefits of blue carbon methods make them a promising component of climate change mitigation strategies.

## Public Debate and Perceptions

Public perception of blue carbon as a mCDR strategy involves a complex interplay of local and global perspectives, socio-demographic factors, and the perceived naturalness of conservation efforts. The findings by (Nawaz, Peterson St-Laurent, and Satterfield 2023) reveal strong public support for restoration efforts that show clear ecological and economic benefits. Blue carbon methods present low ecological risks and numerous benefits, including storm protection, coastal erosion prevention, increased biodiversity, food provision, and support for various human livelihoods (Merk, Grunau, et al. 2022). While social and governance challenges exist, they are generally manageable, especially with equitable distribution of benefits. Public support for ecosystem conservation and positive synergies with existing environmental laws further enhance the feasibility of these approaches.

Organizations such as CANEurope.org have not explicitly endorsed mCDR approaches but emphasizes enhancing the carbon sequestration potential of marine ecosystems. It advocates for protecting environments with blue carbon storage potential and calls for more research into the carbon storage capabilities of marine ecosystems like kelp forests and algae to inform policy with robust scientific data. People favor projects with visible and tangible outcomes, such as mangrove and coastal area restoration as they provide essential services that sustain local livelihoods, and this dependency significantly influences public attitudes toward their conservation and restoration. For example, people who rely on non-extractive uses, like storm protection and nursery habitats for fisheries, tend to support conservation efforts more than those who depend on extractive uses such as timber and fuelwood harvesting (Stone et al. 2008; López-Medellín, Castillo, and Ezcurra 2011; Badola, Barthwal, and Hussain 2012).

Socio-demographic factors also play a crucial role. Education level, awareness of ecosystem services, and socio-cultural backgrounds significantly influence attitudes. Higher education levels are associated with greater awareness and support for conservation (Badola, Barthwal, and Hussain 2012). Urban populations, which might focus more on recreational services, show different preferences compared to rural populations that might rely more heavily on the direct economic benefits from these ecosystems (Vande Velde et al. 2019). Additionally, the method of implementation and the design of benefit-sharing schemes are critical for gaining local support. Trust in local institutions and transparent management practices enhance the acceptability of conservation initiatives (Stone et al. 2008; Badola, Barthwal, and Hussain 2012). The global perspective on blue carbon has recently started to recognize its potential for $CO_2$ sequestration but this emerging interest can sometimes also conflict with local needs and dependencies.

Global initiatives to enhance $CO_2$ uptake through blue carbon ecosystems might clash with the livelihoods of local communities who depend on these ecosystems for their survival. Trust in governance at both local and global levels is paramount for the acceptability of blue carbon strategies. Effective governance, fair benefit sharing, and inclusive management practices can significantly enhance local support. For instance, trust in institutions has been shown to positively influence perceptions of various mCDR strategies, including blue carbon management (Badola, Barthwal, and Hussain 2012; L'Orange Seigo, Dohle, and Siegrist 2014).

In general, the perceived naturalness of blue carbon management significantly impacts its acceptability. Labeling these strategies as natural solutions increases public support, as people tend to view natural approaches as safe and non-destructive. Conversely, methods perceived as engineering or tampering with nature are often viewed more negatively (Hansen 2006). This preference for natural solutions aligns with findings that nature-based solutions like blue carbon management are generally more acceptable than technological interventions (Merk et al. 2019). Conflicts between local and global interests are a significant challenge. Local opposition can arise when global efforts to maximize carbon sequestration through blue carbon management interfere with local land and resource use. The Haida Salmon Restoration Project is an example where local support was divided; some community members supported the project due to the urgent need for climate action, while others opposed it as an external imposition (Gannon and Hulme 2018).

Additionally, the perceived control and containment of mCDR methods influence public acceptability. Strategies perceived as controllable and contained are generally more acceptable. Blue carbon projects, being localized and seemingly natural, tend to align better with public preferences compared to more expansive and less contained approaches. However, it is yet unclear whether payment systems that focus exclusively on carbon sequestration in Blue Carbon Ecosystems (BCEs) will lead to socially optimal outcomes, given the potential trade-offs with other important ecosystem services. It is crucial to design compensation schemes that take into account the full range of ecosystem services provided by BCEs and ensure that all benefits are accounted for and local communities are fairly compensated (Merk, Grunau, et al. 2022). The public perception of blue carbon as a mCDR strategy is shaped by local dependencies, socio-demographic factors, governance trust, and the perceived naturalness of conservation efforts. Bridging the gap between local and global perspectives and ensuring inclusive, transparent management are essential for the successful implementation and acceptance of blue carbon initiatives. Understanding and addressing these nuanced perceptions can enhance the feasibility and effectiveness of blue carbon as a strategy for carbon dioxide removal.

## Assessment by Dimensions

The assessment of Blue Carbon Ecosystems using the ASMASYS assessment framework has identified the potential and uncertainties of these ecosystem-based carbon sequestration measures. A recent discussion (16th TET, 25 - 26th September 2023 / (Warnemuende) focused on a hypothetical scenario starting in the fall of 2025 that envisions the establishment of new kelp forests west of Sylt. This four-year experiment would assess the effectiveness and monitor the side effects to investigate the feasibility of enhancing coastal ecosystems at the local level to sequester carbon dioxide.

**Techno-Environmental Feasibility:** Currently, the infrastructure and technology required for blue carbon initiatives, specifically kelp-based carbon sequestration, are not suitable due to the lack of rocks on the seafloor for kelp to adhere to. Despite this, other geophysical and chemical properties of the environment are favorable and could potentially support kelp growth after modifications to the sea floor. However, the future impact of climate change on the suitability of these modifications remains uncertain.

The **political feasibility** of blue carbon projects, particularly those involving kelp, appears plausible due to their perceived ‘nature-based’ approach. However, local opposition could pose significant challenges. The political feasibility would likely be influenced by public debate. Given the sensitivity of the environment, and the implications of replacing one ecosystem with another, or substantially altering existing ecosystems, these types of mCDR efforts could remain controversial. Additionally, political feasibility may be affected by legal uncertainties and the potential for legal consequences.

**Legal Feasibility:** Legally, kelp-based carbon sequestration projects are theoretically allowed but hinge on specific legal interpretations. These interpretations include whether kelp is considered a native species and whether adding rocks to the seabed is classified as dumping or restoration. Legal precedents, such as the WWF court case, could influence these interpretations.

**Economic Efficiency:** The costs and benefits of blue carbon initiatives are largely unknown. The only identified cost is related to the production and distribution of green gravel. A pilot test is necessary to clarify the cost efficiency, which is currently unclear due to numerous unknowns about the effectiveness of these projects.

**Effectiveness:** There are significant uncertainties regarding the net removal and long-term storage of $CO_2$ through blue carbon projects. Determining effectiveness would be a primary goal of any experiments, but monitoring and verifying long-term storage presents substantial challenges.

**Justice:** The distribution of benefits and burdens from blue carbon projects must be fair, with a focus on the impact on local communities, including tourism, fisheries, and cultural services. These projects could have both positive and negative effects on these communities. Procedural justice elements seem to be addressed, but more information is needed for a comprehensive evaluation.

**Environmental Ethics:** From an ethical standpoint, blue carbon projects are not necessarily adverse but would result in the replacement of one ecosystem with another. It is crucial to study and monitor the impact on connected areas to minimize environmental disruption. The design of experimental areas should aim to reduce any negative impacts.

# 7. Exploring Marine Carbon Storage in Germany

The next chapter provides an overview of the current status and the public debate and perceptions of mCS methods. Additionally, it includes a concise summary of the assessment based on the ASMASYS framework, evaluating each method’s feasibility and desirability. The ASMASYS framework was refined through validation using hypothetical test cases (Chp. 4.4) within ASMASYS, allowing also for identification of uncertainties inherent to each method.

## 7.1 mCS in Deep-sea Crust

### Methodology, Potential and Technology Readiness Level

Marine carbon storage (mCS) in deep-sea basaltic crust is one innovative approach to mitigating carbon dioxide emissions. The idea is to transport and inject captured $CO_2$ into the porous spaces of basaltic rocks beneath the ocean floor, where it reacts with the rocks and forms stable carbonate minerals, essentially locking away carbon dioxide for geological times cales (Bachu, Gunter, and Perkins 1994; McGrail et al. 2017). Deep sea basaltic crust offers vast potential storage capacity, and the mineralization process is thought to be more secure and long-lasting compared to traditional storage methods. On a global scale, it is essential to permanently sequester about 20 Gt of $CO_2$ $yr^{-1}$ by mid-century (IPCC, 2018; P4 model), aiming for a dramatic increase of current mCS capacity. However, large-scale deployment (Gt-scale) of mCS remains unrealized, with globally existing facilities capturing and storing about 40 $MtCO_2$ (Snæbjörnsdóttir et al. 2020) each year, mostly by applying conventional mCS methods. Since 2014, Carbfix injected nearly 0.01Mt $CO_2$ dissolved in water into subsurface pore space of basaltic lavas, where it is mineralized and trapped in porous rocks below an impermeable cap rock (Gislason et al. 2010; Matter et al. 2011; Snæbjörnsdóttir et al. 2017; Gunnarsson et al. 2018). The mCS technology under consideration globally estimates storage capacities of up to 100 000-250 000 Gt $CO_2$ along mid-ocean ridges through the carbonation process, exceeding the amount of $CO_2$ released by burning all fossil fuels (Snæbjörnsdóttir et al. 2020). This involves the reaction of $CO_2$ with Mg-/Ca- silicate minerals in basalt rocks, leading to the formation of carbonate minerals such as calcite, dolomite, and magnesite.

### Public Debate and Perceptions

In terms of international law of the sea, the initial question is whether states are permitted to store $CO_2$ in the deep-sea crusts and, if so, where this can occur. The United Nations Convention on the Law of the Sea (UNCLOS) addresses this question by dividing the sea into different zones, clearly defining the rights of coastal states within each zone. The legality of injecting $CO_2$ into the seabed must be distinguished from whether international law permits exporting it to other states for storage. Article 6 of the London Protocol generally prohibits exporting waste for dumping or incineration at sea or on the seafloor. However, a 2009 amendment specifically addressed cross-border $CO_2$ export for storage. Since this amendment has not been ratified by enough states, it hasn't taken effect. In 2019, signatories agreed to apply Article 6 provisionally, which requires a declaration from each state.

To date, Belgium, Denmark, Kingdom of the Netherlands, Norway, Republic of Korea, Sweden, United Kingdom, Switzerland and South Korea have made such declarations, while Finland is preparing theirs as of September 2022 (IMO, 2024). For Germany to export captured carbon dioxide to these states, it must also make a declaration. Additionally, the provisional application of the amended Article 6 requires specific agreements between the exporting and importing states. Experts believe the legal requirements for marine $CO_2$ storage and export are established, but national authorities will make final decisions. For EU member states, the EU Carbon Capture and Storage Directive permits geological $CO_2$ storage in their territories, EEZs, and continental shelves, as defined by the UN Convention on the Law of the Sea, with each project needing approval from the respective national authority.

## Assessment by Dimensions

Due to more limited information available for this section, it is presented in a more concise format, which allows to focus on the key points without adding unnecessary complexity: Marine carbon storage (mCS) in deep-sea basaltic crust involves injecting captured $CO_2$ into porous basaltic rocks beneath the ocean floor, where it reacts to form stable carbonate minerals. This approach offers vast potential storage capacity and a more secure, long-lasting solution compared to traditional methods. The ASMASYS assessment framework evaluated the feasibility and potential challenges of this technology during the hypothetical test case scenario conducted at the 17th Think and Exchange Tank on February 6-7, 2024, in Berlin. This scenario, starting in 2028 and lasting for ten years, involves the injection and monitoring of aqueous $CO_2$ ($aqCO_2$) in the offshore flood basalts of the Norwegian continental margin, specifically in the Vøring and Møre basins. The insights gained from this hypothetical case are crucial for informing and optimizing real-world applications, particularly in determining the project's environmental and technological feasibility, fairness, justice, and overall treatment of the natural world.

Despite its potential, the technology is still in the early stages of research and faces high uncertainties for field applications, with ongoing investigations on lab- and pilot-scales. The techno-environmental feasibility of this project is complex. While environmental conditions are favorable and technological components are available at varying readiness levels, significant infrastructure development is necessary, and the technology is costly. The main bottleneck appears to be the hub on the German coast, although there might be ways to work around this issue. Infrastructure development, especially hubs, is critical and needs early attention. More information is required to evaluate land-based components.

On the political front, the project seems feasible overall, lacking strong opposition but dependent on handling unavoidable $CO_2$ sources and economic concerns such as carbon credits. Involving cement companies could enhance political feasibility. Legally, the project is assumed to be permissible, with recent changes in German law and the completion of necessary environmental assessments and permitting processes. Economically, the project presents both benefits and costs. Benefits include knowledge gains and potential technological leadership, but operational and investment costs are significant. Transport costs are a concern, suggesting alternative locations like German sandstone for cost-efficiency. Effectiveness depends on project output and testing outcomes, but the concept is generally appealing. Justice considerations highlight a fair distribution of benefits and burdens, although governance specifics remain uncertain. Regarding environmental ethics, the project's impact on nature and humans seems limited under normal circumstances, with risks primarily associated with potential leaks and maritime operations. However, the broader energy production chain is not fully considered in this evaluation.

## 7.2 mCS in deep geological formations

### Methodology, Potential and Technology Readiness Level

Industrial non-avoidable $CO_2$ emissions can be significantly reduced by capturing and storing $CO_2$ underground. The technical realization of $CO_2$ storage involves developing concepts for $CO_2$ transport from onshore sources to offshore storage sites and injection into geological formations. The transportation aspect has not been extensively implemented at a large scale, unlike $CO_2$ storage from locally separated gas. Europe's primary storage capacity is found in North Sea sandstone formations. In the German Exclusive Economic Zone (EEZ), potential storage formations remain partially explored, yet available data indicate sufficient capacity in the deep German North Sea subsurface (Lozan et al. 2023). Total estimates range from 3.6 to 10.4 billion tons of $CO_2$ according to Willscher (2007) and 1.9 to 4.5 billion tons according to (Vangkilde-Pedersen et al. 2009), based on usable pore volume in sandstone structures. Computer models are utilized to simulate $CO_2$ storage at selected sites, with up to 10 million tons per site annually. Actual storage capacity is further limited by factors including economic considerations and regulatory requirements.

### Public Debate and Perceptions

In August 2012, Germany implemented the EU directive on CCS into national law, introducing strict measures through the German Carbon Capture and Storage Act (Kohlenstoffdioxid Speicherungsgesetz, KSpG). This Act presents two main obstacles to $CO_2$ storage in the German North and Baltic Seas: it requires proposals for $CO_2$ storage approval to be submitted by the end of 2016, and it allows federal states to exclude areas from storage. Mecklenburg-Western Pomerania, Lower Saxony, and Schleswig-Holstein have used this right to ban underground $CO_2$ storage in their coastal regions. A 2022 evaluation report highlighted that the current legal framework hinders practical CCS application but noted that CCS and carbon capture and utilization (CCU) technologies could help Germany achieve greenhouse gas neutrality by 2045. The German government is discussing expanding and adapting the CCS Act as part of a broader CMS, aiming to identify applications for CCU and CCS and develop the necessary economic and regulatory frameworks for their rapid implementation. The respective draft law has been filed by the Federal Government in June 2024 (Entwurf zur Änderung KSpG).

A draft amendment to the German Climate Change Act proposes integrating $CO_2$ storage into national climate policy and setting storage targets for 2035, 2040, and 2045. The German federal government has outlined specific measures for further developing the Carbon Management Strategy. Germany will ratify the amendment to the London Protocol to allow $CO_2$ exports for offshore storage and will make the necessary changes to the High Seas Dumping Act (Hohe-See-Einbringungsgesetz). Additionally, Germany may need to connect to storage sites in other EU countries due to the lack of suitable $CO_2$ storage options within Germany soon. To facilitate this, Germany will ratify the relevant amendment to the London Protocol and adjust the national legal framework to permit $CO_2$ exports to offshore carbon storage sites (Carbon Management Strategy - BMWK, 2024).

In March 2023, the EU Commission proposed establishing geological capacity to store 50 million tonnes of $CO_2$ by 2030 under the Net-Zero Industry Act, which identifies CCS as a bridging technology (SWP-Berlin, Die Nächste Phase Europäischer Klimapolitik, 2024; SWP-Berlin, Carbon Management Chancen und Risiken für Ambitionierte Klimapolitik; SWP-Berlin, $CO_2$ Entnahme als Integraler Baustein des Europäischen Green Deal, 2024). This plan requires EU member states to publish data on potential $CO_2$ storage sites and report annually on project progress, with oil and gas companies responsible for exploration and development. Reactions are mixed, with supporters advocating for CCS and critics emphasizing the need to reduce greenhouse gas production. Ongoing debates are expected to lead to new regulations and laws, particularly in Germany. Federal states such as Mecklenburg-Western Pomerania, Lower Saxony and Schleswig-Holstein have completely excluded $CO_2$ storage on their territory due to controversial public and political debates.

In the early 2000s, some CCS-projects in Germany faced strong opposition and were abandoned (Dütschke 2011; Otto et al. 2022). Negative perceptions of the technology are not just driven by factors pertaining to the storage of CO2 such as risk perceptions (L'Orange Seigo, Dohle, and Siegrist 2014) but also by the perception of the emission source. The storage of CO2 from biogenic sources is perceived more favorably compared to emissions from coal-fired power plants (Dütschke et al. 2016; Whitmarsh, Xenias, and Jones 2019; Romanak, Fridahl, and Dixon 2021). With the shift of the debate from using CCS for the abatement of fossil-fuel emissions to the mitigation of hard-to-abate emissions or carbon dioxide removal exclusively (Schenuit et al. 2021), the tone in the media portrayal changed, but the negative association with the fossil-fuel industry lingered on (Otto et al. 2022). Contrary to what a NUMBY-(not-under-my-backyard) hypothesis would suggest study participants do not perceive offshore storage more positively compared to onshore storage (Merk et al. 2022) and the export of CO2 for storage to other countries is viewed more negatively compared to storing CO2 from domestic facilities under domestic territory (Merk, Nordø, et al. 2022; Merk, Andersen, and Nordø 2023).

The current political and institutional regulations do not support the implementation of carbon storage, so geological storage is still at an early stage of political development. This has also implications for CDR approaches that use geological storage, namely bioenergy with CCS (BECCS) and direct air carbon capture and storage (DACCS): while direct air carbon capture technology is being trialed and bioenergy production is well established, carbon storage options are limited, which restricts the use of these CDR methods in Germany. The national climate strategy proposes to assess the CCS potential but does not explicitly call for the introduction of BECCS and DACCS. All mCDR options will be assessed as part of government-funded research.

## Assessment by Dimensions

The assessment of marine carbon storage (mCS) within the ASMASYS framework has revealed both promising potential and notable challenges and uncertainties associated with this technology. In contrast to other sections, which may contain more hypothetical scenarios, this part focuses more directly on the most important points. To implement mCS effectively, suitable storage formations must be identified, and a detailed roadmap developed. This involves reassessing static storage capacity with updated data, quantifying dynamic storage capacities, evaluating potential leakage pathways, and investigating environmental impacts such as seismic noise on marine life. Environmentally friendly monitoring methods, like passive seismic techniques, are under development. Interactions between $CO_2$ storage and other uses must be assessed from ecological, technical, legal, and economic perspectives, with strategies to resolve potential conflicts. At the 19th ASMASYS Think and Exchange Tank on May 23, 2024, the focus of discussion was on mCS in sandstone formations in the North Sea, as investigated in the project GEOSTOR. This assessment was conducted without stakeholder involvement due to less hypothetical nature (higher TRL) of this section and because stakeholder dialogue had already been conducted within the GEOSTOR activities with results reflected in the TET.

**Techno-Environmental Feasibility:** Suitable land and geological formations for storage are available, though further surveys are needed. Local geophysical and chemical conditions are suitable, but more exploration is required. The necessary technologies are at a Technology Readiness Level of 8-9. Infrastructure needs to be built for the German industry, while Norway's infrastructure is near completion. Technical means to manage potential accidents include stopping injections, sealing, and pressure release (such as groundwater discharge). Materials for mCS activities are available, and although material-intensive, availability is not considered a problem. Sufficient low-carbon energy sources for carbon capture are currently lacking, necessitating renewable energy production. Specialized skills, primarily from the oil industry, are available, and skilled workers can be sourced if not locally available.

**Political Feasibility:** Political feasibility is positive with majority support, although challenges and legal possibilities remain. Government-supported research was active until 2019, primarily for land-based methods, with the GEOSTOR project being the first marine initiative. CCS is integrated into EU and national climate policies, with most German political parties supporting it except Die Linke and AFD. Public acceptance is moderate with some NIMBY concerns, particularly for offshore storage near German islands.

**Legal Feasibility:** Currently, permit applications for CCS are not possible in Germany, but legalization efforts are underway (Kohlenstoffdioxid Speicherungsgesetz, KSpG - vom 17. August 2012; Entwurf zur Änderung KSpG - vom 21 Juni 2024). An Environmental Impact Assessment (EIA) is required, though the specific legal basis is unclear. Scoping studies are planned to evaluate environmental monitoring. Alternative options for hard-to-abate emissions are limited, making CCS necessary for offsetting. Public engagement is required, with opportunities to appeal and sue. The activity is currently prohibited due to the classification of the activity as dangerous. There are no direct precedents, but new technologies offer guidance. CCS activities do not overlap with indigenous property rights, but pipelines passing through the Nationalpark Wattenmeer raise concerns.

**Economic Efficiency:** The option entails high costs and the need for subsidies, potentially becoming economically viable only if the EU-ETS price doubles. The marginal removal cost is around €150 - €250 per ton of $CO_2$ (estimation date: May 2024), with hopes for cost reductions. The option is not extremely resource-intensive but will utilize space for pipelines and underground usage. Technological advancements are anticipated, though costs will remain high. Public transaction costs are involved, but no additional private transaction costs other than production costs. Over 30 years, investment costs are smaller than operating costs, but investment is highly specific with no co-benefits. Revenue risks are high due to costs exceeding revenue through EU-ETS, necessitating subsidies. There are no significant monetized damages or benefits to third-party actors.

**Effectiveness:** The mCDR/mCS option is highly effective for long-term storage with significant potential, though it needs time to scale. It can store 20-40 million tons of $CO_2$ per year in the German EEZ, reaching full potential effectiveness in roughly ten years. The method does not remove other non-$CO_2$ GHGs. Life cycle emissions are significant due to high energy needs but depend on the energy source, which may be mostly renewable by the time the option is underway. The carbon sequestration reservoir works on geological timescales, essentially forever. The risk of storage leakage is small under good regulation, with over 99% of the $CO_2$ remaining stored. User errors are possible but unlikely. Net $CO_2$ removal is monitored with low uncertainties. The CCS activity does not cause indirect changes in seasonal $CO_2$ fluxes or regional albedo. Once the activity stops, $CO_2$ remains stored.

**Justice:** Relevant information about CCS activities is publicly accessible. Affected individuals can participate in decision-making, with democratically elected bodies involved at every stage. Industrial noise produced by seismic exploration, shipping activities as well as the construction of underwater pipelines may impact porpoises. The CCS method does not affect local freshwater availability. It requires minimal sea floor space for burying a pipeline but significant subsurface space and space for coastal hubs. Conflicts with marine area uses are managed through spatial planning. The activity poses no health risks and will create new jobs, especially in the oil and gas industry, without threatening existing ones. It does not significantly affect ecosystem provisioning or cultural services. Environmental impacts are monitored with required EIAs, and no unknown impacts are expected. There are no additional human impacts except for a potential rise in cement prices. There are no specific burdens for the Global South, and the distribution of burdens at national or European levels is not specified.

**Environmental Ethics:** The option has minimal impact on the natural world due to potential small-scale leakage events. Local biodiversity may be affected in the case of small-scale leakages in a range of about $50m^2$ around a leakage, but no extinctions are expected. There will be no changes in air quality or surface water quality. Bottom-near pH may decrease, and sediments and bottom water quality may change in case of leakage. Local ocean circulation, primary production, and food web dynamics will not be affected, except locally in the case of leakages. Pipelines may impact seabed biospheres and habitat integrity up to 2km depths (deep biosphere). Immobile organisms within $50m^2$ surroundings may die. There is no increased risk of invasive species, and ecosystems are expected to adapt, with $CO_2$-tolerant species dominating. Overall ecosystem functioning will not be significantly impacted. After stopping the activity, the situation will normalize. There will be no effects on local climate or influence on regulating services such as air purification, climate regulation, and coastal erosion protection.

# 8. Conclusion

The ASMASYS (Unified Assessment framework for proposed methods of Marine CDR and interim knowledge Synthesis) project has provided comprehensive insights into the assessment of marine carbon dioxide removal (mCDR) and marine carbon storage (mCS) technologies, highlighting both great potential and challenges. Our assessment results underscore the critical importance of detailed knowledge and robust assumptions in evaluating the feasibility and desirability, including potential impacts of the options assessed. The Think and Exchange Tanks on specific test case scenarios may function as a supportive instrumentation in navigating the high demand and uncertainty surrounding these technologies, revealing crucial insights into site-specific potentials and limiting factors.

The central purpose of the ASMASYS framework is to help guide wider debates about what mCDR/mCS options could play a role in overall policy strategies to respond to climate change and which mCDR/mCS options should play a role. It presents no way to decide these debates, no formula that tells actors what to do. But it collects and structures the relevant issues and questions decision makers and ultimately the wider public must consider in making their decisions. It offers assistance for relevant actors to develop their own perspectives on mCDR/mCS, rather than offering a perspective of its own. Its scope is holistic insofar as it aims to offer said assistance at various stages of mCDR/mCS development and implementation. It can be used to assess the possibility and the merits of a small-scale research project as well as the possibility and merits of a massive mCDR/mCS implementation strategy - and to highlight the open questions and uncertainties we are faced with in either case. Also, it should be broad enough to cover various mCDR/mCS methods and help to assess their differences and their communalities. The key to reaching such width is the absence of a ranking or weighting system that tells users how the individual verdicts on various criteria and dimensions combine. Such formulas, if they are ever convincing, are only convincing when designed for specific objects of assessment in specific circumstances. By “merely” collecting and structuring the issues and questions of an assessment, the ASMASYS framework can be used to assess a far wider variety of mCDR/mCS options.

In future work, we aim at further generalizing the criteria to assess and compare various mitigation and geoengineering options. We designed the overall structure of the framework to allow for that. One overarching finding is that there are substantial knowledge gaps, and these often preclude a conclusive assessment of mCDR and mCS options. We do not see this as evidence that an assessment framework for these options is of rather limited use. Instead, the framework highlights what (kind of) information is missing for a conclusive assessment and thus helps to guide future research and decisions on research funding opportunities.

While efficiency and feasibility assessments are pivotal in deciding whether restoration projects fall under carbon dioxide removal (CDR) frameworks, the focus of ASMASYS remains on exploring viable mCDR/mCS applications distinct from ecosystem restoration.

Looking ahead, conceptual new directions in assessment framework research, including insights from social sciences and philosophical reflections, promise to enrich future evaluations. Additionally, a deeper examination of current EU and German environmental standards could enhance existing criteria and indicators for evaluating environmental impacts, ensuring robust frameworks for future assessments. By delineating pathways for future research and emphasizing the importance of methodological rigor and informed decision-making, this endeavor sets a foundation for sustainable climate action in the years to come.

# 9. Acknowledgement

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Your expertise and dedication have greatly enriched this project, and we deeply appreciate your contributions.

# 10. Glossary

| | |
|---|---|
| COP21 | 21st Conference of the Parties |
| AWL | Accelerated weathering of limestone |
| BECCS | Bioenergy with Carbon Capture and Storage |
| BC | Blue Carbon |
| BCEs | Blue Carbon Ecosystems |
| $Ca(OH)_2$ | Calcium Hydroxide |
| CCS | Carbon Capture and Storage |
| CCU | Carbon Capture and Utilization |
| $CO_2$ | Carbon Dioxide |
| $CO_2e$ | Carbon Dioxide Equivalents |
| CDR | Carbon Dioxide Removal |
| KSpG | Carbon Dioxide Storage Act |
| CMS | Carbon Management Strategy |
| CEW | Carbon Electrolysis with Water |
| DACCS | Direct Air Capture of Carbon and Storage |
| EIA | Environmental Impact Assessment |
| EU ETS | EU Emissions Trading System |
| EEZ | exclusive economic zone |
| BMWK | Federal Ministry for Economic Affairs and Climate Action |
| KSG | German Climate Protection Act |
| GHG | Greenhouse Gas |
| HSEG | High Seas Dumping Act |
| ICM | Industrial Carbon Management |
| IPCC | Intergovernmental Panel on Climate Change |
| IMO | International Maritime organization |
| LOHAFEX | Iron Fertilization Experiment (AWI) |
| LCA | life cycle assessment |
| LNe | Long-term Strategy for Negative Emissions |
| mCDR | marine Carbon Dioxide Removal |

| | |
|---|---|
| mCS | marine Carbon Storage |
| $CH_4$ | Methane |
| Mt/yr | Mega Tonnes per year |
| MRV | Monitoring, Reporting and Verification |
| NETs | Negative Emission Technologies |
| NZIA | Net Zero Industry Act |
| $N_2O$ | Nitrous Oxide |
| NGOs | non-governmental organization |
| NIMBY | Not In My BackYard |
| OAE | Ocean Alkalinity Enhancement |
| SWP-Berlin | Stiftung Wissenschaft und Politik (SWP) |
| TRLs | Technology Readiness Levels |
| Tg C | Terragram of Carbon |
| UNCLOS | United Nations Convention on the Law of the Sea |
| WWF | World Wide Fund For Nature |

# 11. Links/Protocols/Press Releases

https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2024/05/20240529-cabinet-clears-path-for-ccs-in-germany.html

https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2024/05/20240529-cabinet-clears-path-for-ccs-in-germany.html

https://www.bmwk.de/Redaktion/DE/Downloads/E/eckpunkte-der-bundesregierung-fuer-eine-carbon-management-strategie.pdf?__blob=publicationFile&v=2

https://www.bmwk.de/Redaktion/DE/Downloads/E/240226-eckpunkte-negativemissionen.html

https://www.bmuv.de/faqs/kohleausstiegsgesetz

https://www.epa.gov/sites/default/files/2015-10/documents/lpamended2006.pdf

https://www.gesetze-im-internet.de/kspg/

https://dserver.bundestag.de/btd/20/119/2011900.pdf

https://www.gesetze-im-internet.de/hoheseeeinbrg/

https://www.theguardian.com/uk-news/2023/apr/17/protesters-urge-caution-over-st-ives-climate-trial-amid-chemical-plans-for-bay-planetary-technologies

https://www.europarl.europa.eu/news/en/press-room/20240223IPR18078/nature-restoration-parliament-adopts-law-to-restore-20-of-eu-s-land-and-sea

https://www.dena.de/newsroom/publikationsdetailansicht/pub/kurzgutachten-im-rahmen-der-dena-leitstudie-aufbruch-klimaneutralitaet/

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# 13. Supplement: indicators and criteria

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| I01 | Impacts on air quality | Will there be changes in air quality? (i.e. regional concentration threshold of ground level ozone levels, particle pollution, sulfur dioxide and nitrogen dioxide) |
| I02 | Impacts on surface water quality | Will there be changes in seawater (surface water) quality? (i.e. Changes in nutrients, oxygen, heavy metal concentration and sedimentation in the seawater due to mCDR measure) |
| I03 | Impacts on marine water quality | Will there be changes in seawater (marine water) quality? (i.e. Changes in nutrients, oxygen, heavy metal concentration and sedimentation in the seawater due to mCDR measure) |
| I04 | Impacts on ground water quality | Will there be changes in sea water (ground water) quality? (i.e. Changes in nutrients, oxygen, heavy metal concentration and sedimentation in the seawater due to mCDR measure) |
| I05 | Impacts on the chemical and physical quality of soils (marine sediments and land) | Are there changes in nutrient (e.g., N, P) , oxygen, heavy metal concentration, and sedimentation in the runoff water, water body, soil or sediments due to CDR measure? |
| I06 | Impacts on net effects of audible noise on humans and ecosystems | Are there any impacts on humans and non-humans from audible noise caused by the mCDR measure? (Env Ethics) |
| I07 | Impacts on local ocean circulation | Does the deployment of mCDR X method affect local ocean circulation? |
| I08 | Impacts on local and global biodiversity | Will the option affect local or global biodiversity? (Leg) |
| I09 | Impact on ecosystem primary production | Does the option impact local primary production/ecosystem productivity? |
| I10 | Impact on food web dynamic | Does the option impact maintenance of food web dynamics? |
| I11 | Impact on habitat provision species | Are there impactings on habitat provisioning species (e.g., biogenic habitats, such as marine or terrestrial plants, and sponges, corals which provide habitat for species)? |
| I12 | Impact on habitat for breeding | Does the option impact breeding for species in the ecosystem? |
| I13 | Impact on habitat integrity | Does the option impact the integrity of the habitat? |
| I14 | Impacts on risk of invasive species | Does the option increase the risk of invasive species? |
| I15 | Impacts on ecosystem resilience | If the ecosystem is negatively affected by the option, will the ecosystem be able to adapt (ecosystem resilience)? |
| I16 | Impacts on ecosystem functioning | Concluding the questions on ecosystem primary production, food web dynamics, habitat provision species, habitat for breeding, habitat integrity, risk of invasive species, ecosystem resilience: Are there impacts on the ecosystem functioning? |
| I17 | Reversibility of the impact | To what degree will the aggregated set of anticipated or unanticipated impacts be mitigated/reversed after the end of the mCDR activity? |
| I18 | Impacts on local freshwater availability | Does the deployment of mCDR X method alter the local freshwater availability (e.g., changes in groundwater/aquifer levels due to CDR measure)? |

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| I19 | Animal fatalities | Will the option cause the death of animals and, if so, of which animals and how many of them? |
| I20 | Impacts on local climate | Are there effects on local climate that are related to biophysical effect/s<br>(e.g. radiative forcing)? |
| I21 | CO2 sequestration and storage | How much $CO_2$ per year can this mCDR pilot test remove from the atmosphere and store/sequestrate durably? (Econ) |
| I22 | Changes in rate of CO2 removal over the year (Δ CO2 /y) | Is the rate of (permanent) $CO_2$ removal (and storage) from the atmosphere stable or changing over time (increases / decreases over time), within the time period of the project and after? (Econ) |
| I23 | Lead-up time for full potential of removal rate | How long does it take to reach the full potential effectiveness (max removal rate)? (Econ) |
| I24 | Removal potential of other GHGs | Does the mCDR method remove other (non-$CO_2$) GHGs from the atmosphere?<br>(Econ) |
| I25 | Life-cycle emission of GHGs | What are the life cycle emissions of the pilot study? (Econ) |
| I26 | Natural persistence of storage | At the current climate state, on what time scale does the carbon (sequestration) reservoir work/ For how long can $CO_2$ be actively removed? (Econ) |
| I27 | Risk of losing carbon due to natural perturbation | How high is the risk of storage leakage (or re-release of $CO_2$) due to natural perturbation (i.e. storms)? (Econ) |
| I28 | Risk of losing carbon due to man-made perturbation | How high is the risk of losing stored carbon due to man-made perturbations (including anthropogenic climate change)? (Econ) |
| I29 | Emissions persist after the termination | What is the risk of any remaining emissions taking place should we decide to stop X? (Leg, Econ) |
| I30 | Changes of $CO_2$ fluxes | Does the mCDR activity cause indirect/undirected changes of seasonal $CO_2$ fluxes (either uptake or emission) compared to the baseline? |
| I31 | Changes of GHG fluxes | What are the (indirect) changes of GHG fluxes (either uptake or emission) compared to the baseline? |
| I32 | Changes in albedo | Is regional albedo affected? |
| I33 | Climate consequence of stopping the CDR | Is there a risk of an increasing speed of warming in the case of termination?<br>(Leg, Econ) |
| I34 | Geophysical and chemical local conditions suitability | Are the geophysical and chemical local conditions suitable? |
| I35 | Habitat suitability for biological components | If applicable, is the habitat suitable for the bio-based components (e.g., kelp)? |
| I36 | Geological resources availability from the land and sea. | If applicable, is suitable land and/or geological formations available for storage? (Econ) |
| I37 | Current and potential future infrastructure capacity along the supply chain | Do necessary infrastructures already exist? If not, can we create those first? (e.g., energy grid, roads, pipelines) (Econ) |

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| I38 | Material resource availability | Is the material required for this mCDR activity available, possible to produce, or must be bought/taken from somewhere else? (Econ) |
| I39 | Energy availability | Are there enough low-carbon energy sources for the mCDR option X? (Econ) |
| I40 | Area demand on land and sea | What is the percentage of land/sea area in the region additionally used, and the increase in area demand per year? |
| I41 | Work skills amount and competences | What kind of specialized skills do workers need for this work and are they available? (Econ) |
| I42 | Possibility to recruit skilled workers | If no skilled workers are availble locally, can they be sourced from elesewhere? |
| I43 | Conflicts or competition with existing and alternative marine spatial planning and other uses | Are there conflicts with existing uses of the marine area such as shipping routes, fishing grounds? (Pol, Leg) |
| I44 | Maturity of mCDR approach | How mature are the technologies necessary for mCDR option X? (Econ) |
| I45 | Expected technological progress | Will technological advancements occur? |
| I46 | Risk management capacity in the facility | Is there (technical) risk management capacity to deal with potential accidents? (Leg) |
| I47 | Human fatalities & health impacts | Do we foresee health impacts on humans due to the option (positive or negative)? (Econ) |
| I48 | Impact on employment | Will new jobs be created by the option? Are existing jobs threatened by it?<br>(Econ) |
| I49 | Impact on provisioning services | Will there be influence on ecosystem provisioning services (wild catch fishery, farmed fishery, biotic raw material)? (Env Ethics) |
| I50 | Impact on cultural services | Will there be an effect on an ecosystem's ability to provide cultural services (Leisure, recreation and tourism, aesthetic experience, inspiration for culture, art and design, cultural heritage, cultural diversity)? |
| I51 | Impact on regulating services | Will there be any influence on regulating services (air purification, climate regulation, disturbance prevention and moderation, regulation of water flows, waste treatment and assimilation, coastal erosion protection, biological control, migratory and nursery habitat, gene pool protection)? |
| I52 | International distribution of impacts on people | Global Level (if applicable): Will there be burdens for people in the Global South? How severe will they be? |
| I53 | National distribution of impacts on people | Global Level (if applicable): Will there be burdens for people in the Global South? How severe will they be? |
| I54 | Other harms & benefits for humans | Will the activity have impacts (positive & negative) on humans not covered by the other indicators? (Econ) |
| I55 | Marginal removal costs | Marginal Removal Cost: How much needs to be spent to remove one additional metric ton of CO2? As a proxy to derive the MRC serve the operational costs for running the mCDR measure. |

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| I56 | Opportunity cost | Opportunity Cost: Are there foregone alternative uses of the deployed production factors? |
| I57 | Expected cost reductions | Can cost reductions be expected? - by Economies of Scale (decreasing average production costs per unit of cdr when cdr is scaled up), by learning-by-doing effects in the production process (that decrease average production costs per unit of cdr), or by economies of scope (marketable by-products)? |
| I58 | Public transaction costs | Public transaction costs: Are there costs for implementation, MRV, and enforcement of regulations that accrue on the side of the public administration? |
| I59 | Private transaction costs | Private transaction costs: What costs are there other than production costs for private actors (for complying with regulations, for using the market, for insuring against risks, for MRV...)? (Existence of accounting schemes and integration in the EU ETS influence these costs.) |
| I60 | Capital intensity | Capital intensity: How much is the share of capital cost (expenditure to buy, maintain, or improve its fixed assets for applying the mCDR option) in total costs? (Pol) |
| I61 | Investment specificity | Investment Specificity: Are there conceivable alternative applications of the investment or is the investment highly specific? (Pol) |
| I62 | Revenue risk | Revenue Risk: How big is the risk that revenues fail to accrue once the investment is made? This is connected to the expectations on carbon prices. |
| I63 | External effects | External Effects: How much monetized damages/benefits to third party actors caused by the mCDR activity are there? Do corresponding compensation schemes exist? (Jus, Leg) |
| I64 | Public availability of information about previous experiences with similar options | Is relevant information about previous experiences with similar options made publicly accessible? (Pol) |
| I65 | Public availability of information about decision making process | Is relevant information about decision making process made publicly accessible? (Pol) |
| I66 | Involvement and influence of democratically-elected governance bodies in the decision making process | To what extent are democratically-elected governance bodies involved in the decision-making process about the mCDR activity? (Pol) |
| I67 | Representation of (potential) climate victims in decision making process | Do people affected by the (positive and negative) effects have a say in the decision-making process? (Pol, Leg) |
| I68 | Performance of EIA | Has an EIA been done and at what level of quality was it executed? |
| I69 | Quantification of $CO_2$ fluxes and uncertainty of measurement | Is the net amount of $CO_2$ removed from the atmosphere monitored and what are the uncertainties of the measurement? |
| I70 | Quantification of other GHG fluxes and uncertainty of measurement | Is the amount of other GHG fluxes monitored and what are the uncertainties of the measurement? |
| I71 | Monitoring of environmental impacts and uncertainty of measurement | Are environmental impacts monitored and what are the uncertainties of the measurement? (Env Ethics, Pol, Jus) |

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| I72 | Administrative capacity/existence of (national) institutional arrangements to implement mCDR regulation | Is there (national) administrative/institutional capacity to transparently implement and verify the mCDR accounting scheme? (Econ) |
| I73 | Quantification ability of life cycle emissions & its uncertainty. | Is it possible to to quantify the GHG emissions in the life cycle of deployment? |
| I74 | Alternative options for reaching same results | Are there alternative options for reaching the same results? |
| I75 | Restrictions on the substances used | Does the activity involve the use of dangerous/restricted/prohibited materials? |
| I76 | Restrictions on the process used | Does the activity involve the use of dangerous/restricted/prohibited processes? |
| I77 | Impact on cultural heritage | Will cultural heritage/natural monuments including those underwater be affected? |
| I78 | Impact on indigenous rights | Is the activity area overlapping with indigenous property or rights? |
| I79 | Respect of rights | Does the activity respect protected rights? (Pol, Jus) |
| I80 | Existence of dedicated regulation | Is the activity directly regulated/prohibited at any applicable level of law? |
| I81 | Existence of jurisprudence | Have there been any court cases about related issues in the past that might provide guidance on what is allowed/not allowed, even if there are not clear laws in place? |
| I82 | Existence of contract for dispute settlement | Is there a contract for dispute settlement? |
| I83 | Reference to mCDR by members of government/parliament etc. | Is there government supported research into mCDR? |
| I84 | Inclusion of mCDR in EU/national government climate strategy documents/communications | Has mCDR begun to be mentioned in national/regional (EU) climate policy documents? (Econ) |
| I85 | Level of heterogeneity/polarization between relevant political actors' (and relevant publics?) positions on/perceptions of mCDR | Is there an open political debate about mCDR in Germany? Do political parties (and their constituencies) in Germany support or oppose mCDR? |
| I86 | Level of volatility of political actors positions on mCDR (waves of opening and closing of the debate and shifting position building) | Have political actors often changed their positions on mCDR? (Econ) |
| I87 | Incorporation/codification of mCDR in national/EU climate law | Has mCDR been integrated into national/regional (EU) climate policy? (Econ) |
| I88 | Inclusion of mCDR in regional and/or international climate/carbon accounting scheme | Is there a politically institutionalized regional/international (EU/IPCC) CDR certification/accounting scheme that covers mCDR? (Econ) |
| I89 | Integration of mCDR in carbon market (EUETS) | Has mCDR been included in a carbon market (e.g. EU ETS)? |

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| I90 | Perception of mCDR in general public | How does the general public perceive the activity and is there the potential for political support or opposition? |
| I91 | Perception of mCDR in directly affected public | How does the locally affected public perceive the activity and is there the potential for political support or opposition? |