ASMASYS

ASMASYS – Assessing Marine Carbon Removal: Synthesis, Scenarios and Governance

Foresight Workshop Report: Ocean Alkalinity Enhancement Scenarios for Germany in 2040

Milestone 1.1.1 // Miranda Boettcher

CDRmare

DAM GERMAN MARINE RESEARCH ALLIANCE

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This report outlines processes and insights from a participatory foresight workshop held in May 2025 at the SWP in Berlin, supported by the German Federal Ministry of Research, Technology and Space (BMFTR) grant number 03F0962C. The report represents the author(s)' summary of and reflection on the workshop and does not necessarily represent the views of the participants or organizations involved.

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1. Introduction

Background on mCDR & OAE

Since net zero greenhouse gas emissions targets have become a keystone of climate policy, there has been increasing debate about the need to actively remove carbon dioxide from the atmosphere in addition to reducing emissions (Schenuit et al. 2022; IPCC 2022) to produce anthropogenic negative emissions.

The ocean already plays a key role in regulating the global climate by absorbing a large proportion of anthropogenic carbon dioxide emissions (Watson et al. 2020: Friedlingstein et al. 2022). As the technical and political challenges of the land-based carbon dioxide removal approaches are becoming more apparent, the oceans seem to be becoming the new »blue« frontier for marine carbon dioxide removal (mCDR) approaches (Boettcher et al. 2021; Boettcher et al. 2023).

One of the proposals being investigated in Germany and elsewhere for enhancing the carbon drawdown and storage potential of the ocean is Ocean Alkalinity Enhancement (OAE), which involves adding alkaline minerals – like ground lime or olivine rock – to the ocean, which then react with CO_2 and water to form bicarbonate and carbonate ions, thus enhancing the carbon storage capacity of seawater (Guo et al., 2024; see also Figure 1).

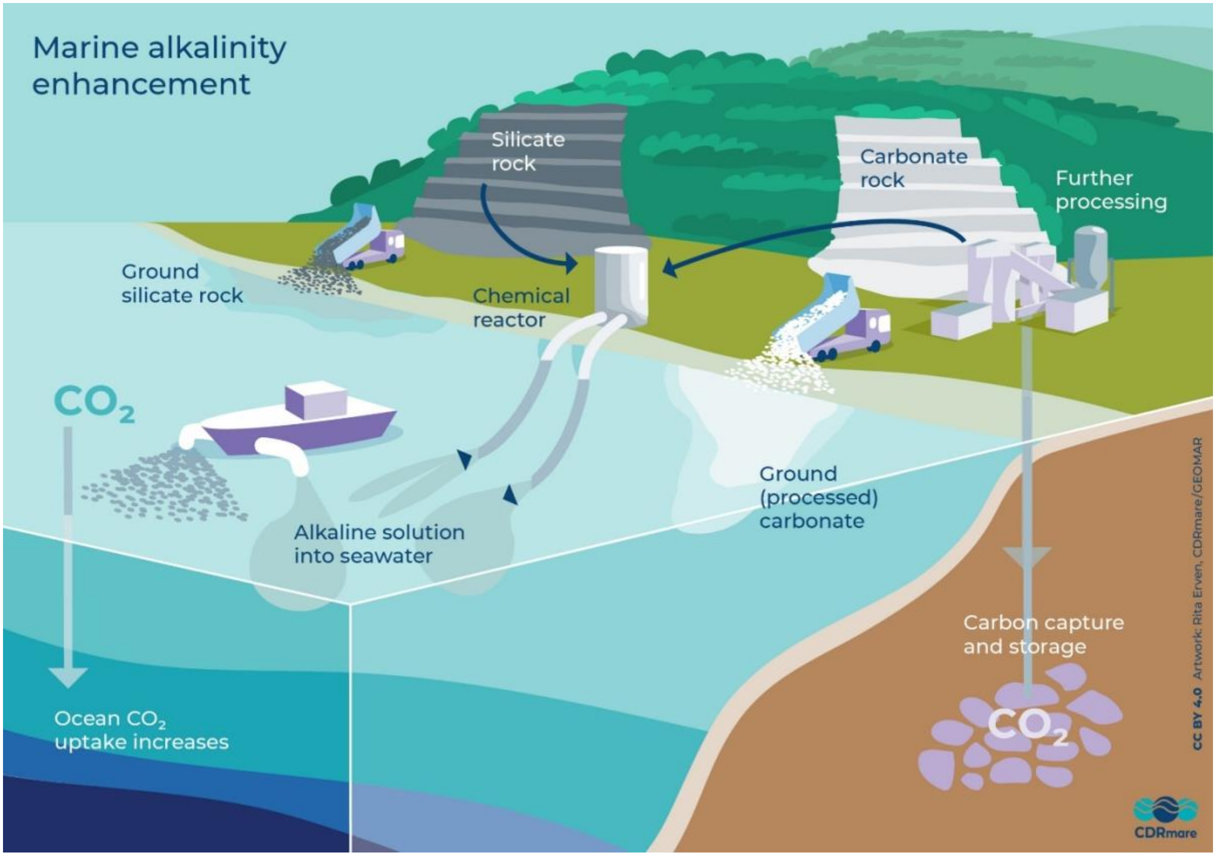


Figure 1: Marine or ocean alkalinity enhancement. © Rita Erven, CDRmare/GEOMAR.

Workshop aims: Developing qualitative scenarios to explore OAE futures for Germany

The foresight workshop described in this report was carried as part of work on a BMBF-funded research mission on marine CO_2 removal called: »CDRmare: Marine carbon sinks in decarbonisation pathways«. The research mission investigates how the carbon drawdown and storage effect of the ocean may be enhanced in the future. The objectives of the mission are: to explore and assess various marine approaches to atmospheric CO_2 removal (mCDR) in terms of their potential and environmental, economic, social and political impacts and risks in the context of responsible and sustainable use of the ocean and; to provide information to policy makers and society on future opportunities and risks of marine CO_2 removal approaches and their governance.

One of the proven methods for exploring plausible futures is the development of qualitative future scenarios. The development of such scenarios on the topic of OAE cannot be a purely academic endeavour, but should involve decision-makers from the administration as well as other relevant actors from science and civil society. A two-day foresight workshop was therefore held on May 12 & 13 2025, to enable relevant actors to engage in an exploratory process to develop plausible future scenarios OAE scenarios for Germany.

The workshop aimed to switch the mode of thinking about the future of OAE in Germany from predictive to anticipatory: a reorientation from »navigating ›what will be‹« to »thinking through alternative ›what ifs?‹« (Boettcher et al. 2016; Boettcher 2023). The workshop organisers aimed to encourage the participants to engage experimentally with conceptions of the future derived from a broad field of perspectives.

The event was designed to apply a **participatory foresight method** – namely, the construction of qualitative scenarios – to enable structured thinking about complex systems and possible futures containing many unknown unknowns. The workshop furthermore made use of **explorative** scenarios, which focus on the broader context of a topic in order to explore alternative future environments. These lie in contrast to strategic policy planning scenarios, which are designed to plot alternative courses of action and their consequences. Explorative scenarios trace the complex interactions of a broad range of political, economic, technological, and social factors in a variety of hypothetical futures. They act as hypothetical thought experiments that deal with alternative assumptions about a wide range of developments in the future. Thus, they are context-dependent, subjective and **no not predict probable futures** (Gabriel 2014).

Qualitative scenario development processes are designed to draw upon inputs from multiple disciplinary perspectives, as well as alternative assumptions, expectations, and worldviews from policymakers and stakeholders. As individual biases can lead to one-sided or linear-extrapolative thinking, such scenarios are best constructed in a participatory process of group communication. A methodologically sound process for participatory scenario construction promotes critical reflection of the scenario development process and allows for intersubjectivity, contributing to shared meanings and understandings and thus widening the range of plausibly imaginable futures. Participatory scenario construction thus provides a platform for structured communication that facilitates inter- or transdisciplinary thinking about possible futures. (Gabriel 2014: 5 – 7).

The qualitative foresight process implemented at this workshop was designed applied in this workshop was conceptualised and facilitated by Dr. Johannes Gabriel and Marcel Hadeed from the organisational consultancy Foresight Intelligence (FI) to provide a platform for structured communication about a range of **logically consistent** and **plausible** futures. A consistent scenario is composed of logically coherent **factor projections** that, taken together, describe a future situation. A plausible scenario also provides a credible and comprehensive illustrative trajectory that leads to a consistent future situation, exemplifying the changes necessary to end up in a certain future situation. A qualitative scenario threfore is not only a **picture of the future**, but it also includes a rich ›**history**‹ **of the future** – a pathway which describes how to get to that imagined future (Gabriel 2014: 3).

The workshop planning team set **two broad guiding conditions** for the participants. The first was the **scope** of the OAE futures being discussed, which was set to focus on **the German context**, but taking wider the EU climate policy landscape into account. This choice was made as German climate policymaking is highly embedded in and dependent on EU climate policymaking (Knodt et al. 2020)[1]. Secondly, the **timeframe** for the scenarios was set to the year **2040**. This choice was made based on the current expected timelines for German and wider EU climate policy, which stipulate that Germany should reach net-zero greenhouse gas emissions by 2045 and net negative emissions in 2050 (Presse- und Informationsamt der Bundesregierung 2023). Therefore, the assumption put forward by the organisers was that key decision-making processes on the potential role of OAE in climate policy would be initiated before 2040.

The workshop planning team also made choices about the types of participants to invite to the workshop. Such choices have a significant effect on the workshop outputs, given that – as described above – participatory scenario development processes are designed to draw upon the various knowledge types, perspectives, assumptions, expectations, and worldviews of those involved. The outputs of such processes can thus only be as diverse as the range of voices in the room. The workshop organisers aimed to invite a range of participants from relevant regulatory bodies, as well as representatives from academia and civil society[2].

The following sections outline the participatory scenario development process (section 2), provide detailed descriptions of the resulting scenarios (section 3), and detail comparative reflections on all scenarios developed (section 4).

2. Participatory scenario development process

Exploring the broader context

The first step of the scenario development process was initiated before the workshop began. The participants were first sent an ›environment scanning‹ survey. This asked them to identify a broad range of political, economic, social, technological, environmental, and other factors that could shape OAE policy development in the next 20-odd years. (See annex »FL OAE 2040« for full list of factors listed by

[1] Despite this focus on the German/EU context, linking to the wider context of global emissions scenarios and international climate targets was unavoidable. The group was encouraged to also consider future external influences on EU and German climate policy ambitions.

[2] See Annex for the anonymized list of participants. Despite the organizers' best efforts, civil society was under-represented at the workshop. See section 4 for a reflection on how this may have influenced the scenario development process.

participants). The resulting collection of factors was then clustered into **sets of factors** for the next step of the process (see annex for a map of all factors and how they were clustered).

Narrowing down to key uncertainties

Following an expansive first compilation of factors, a second survey was circulated in which the participants conducted an uncertainty-impact analysis to reduce complexity and select »key uncertainties«. This process is designed to identify factors that (in the participants' collective estimation) have a **very high potential impact** on the future of mCDR, and whose plausible future outcomes have a significant range or spread, meaning their outcomes are **very uncertain**. Using an online assessment tool designed by FI, the participants were asked **rate the uncertainty and impact** of each of the clustered 30 sets of factors gathered during the environment scanning survey. When they met in person on the first day of the workshop, the group was then presented the consolidated results of their joint ranking, and following several rounds of discussions, **agreed upon five highly ranked ›key uncertainties‹** to continue to work with (See annex for the ranking of all the factors).

No.	Title
KU1	Political will and support for OAE
KU2	Economic incentives to undertake OAE
KU3	International cooperation on climate mitigation
KU 4	Environmental side effects of OAE on marine ecosystems
KU5	Legal allowance for OAE activities and limitations on alkalinity substances
KU6	Social perception of OAE

Table 1: Key uncertainties

Creating projections for key uncertainties

In small breakout groups, participants then developed at least four distinct outcomes for each key uncertainty in 2040 – a set of »projections« intended to cover the full spectrum of alternative plausible future states of a given key uncertainty. For this activity, the participants were asked to focus on each key uncertainty in isolation from all other factors, and try to imagine (at least) four possible outcomes of that factor in 2040 that were mutually exclusive, comprehensively exhaustive (MECE). Rather than thinking about likely future states of their factor, the groups were asked were to come up with a wide range of plausible future states of their respective factor, and reminded that a plausible future state is not to be confused with probable future state. Each group was asked to present their factor projections to the plenary, where they were then discussed, and in some cases adjusted within the larger group. The resulting sets of factor projections are outlined in the table below.

No.	Title & description	Projection A	Projection B	Projection C	Projection D	Projection E
KU1	**Political will & political support**: Political ecosystem, parties, parliament, & government. Excluding civil society. Political will = there is a general intent to support OAE. Political will is affected by lobbying, but not included in this factor. Political support = there is legislation & regulation in place to support OAE.	**Strong will & strong support**	**Strong political will & not much support**	**No political will & no support**	**No will & political support changing over time**	
KU2	**Economic incentive/profitability:** What is the price paid for OAE in relation to the cost? Pure technical costs. And one including MRV & potential damages (latter borne by the whole society? I. e. through subsidies for damage to fisheries).	**Not profitable:** Price is below technical costs: OAE would only be done if there were other incentives for doing so.	**Profitability** depends on who is paying: Price is between technical and overall cost (including MRV + compensation for damages). Profitability depends on who is playing for potential damages + MRV. If all of society is paying, it is ›profitable‹. If the companies have to pay themselves, it is not.	**Profitable:** Price is higher than technical costs plus MRV+ potential damages.	**Fluctuating profitability:** Average price is higher than technical +MRV, but **profitability is fluctuating or every hard to predict** (this would mean the average price over all would have to be higher to balance).	
KU3	**International cooperation and governance on climate**: Development of strength of international bodies.	**Powerful** global cooperation and governance. Strengthened UN bodies.	BAU. Ups and downs. **Weak** governance. Some global agreements (PA etc.)	Lack of global governance (no COPs etc), but **regional or plurilateral cooperation** formats. In collaboration with tariffs policy.	**Zero cooperation**. Dissolution of all relevant bodies. Direct geopolitical confrontation is possible under this projection.	
KU4	**Environmental side effects** on marine ecosystems. Positive/Negative/high low.	**Positive side effects, high impact.** (i. e. pH increase, counteracting acidification, increasing biomass)	**Positive side effects, low impact**	**Negative side effects, low impact**	**Negative side effect, high impact**: (i. e. Collapse of the food web, toxic substance release. Increase in toxic algae. Precipitation.)	

KU5	**Legal permissibility/legal allowance** Only research vs. implementation. Substances allowed – only purified alkaline materials vs. all possible materials allowed.	**No OAE activity is legally allowed in the ocean.** Only lab research for OAE.	Research can be done, but only with pure materials	Only research can be done in the ocean, but with all possible materials	Deployment can be done, but only with purified alkaline materials.	Deployment is legally allowed, with all possible materials
KU6	**Social perception** Local/coastal population vs. general population of Germany's perception of OAE	**»Not in my Germany«** General & coastal public against	**»Not in my backyard«** Costal population rejects OAE, General public for	**Only local/costal acceptance** of OAE, general public against	**General & coastal public supports** OAE	

Table 2: Factor projections

Creating scenario frameworks

Participants then created a set of three scenario frameworks. Each scenario framework included one projection from each of the key uncertainties. Even with only four to five projections for each key uncertainty, there were a huge range of possible scenario frameworks. However, not all of them are conceptually consistent; certain projections could be mutually antagonistic. Consequently, the aim was to identify **logically consistent scenario frameworks**. Given the relatively small size of the group and the number of projections involved, this was done via group discussion in plenary. To begin constructing each scenario framework, one participant was selected to pick a projection to start from in the above factor projection table. The moderator then went around the room allowing others to volunteer to pick the subsequent projections from different factors in turn, always having to explain why and how their choice was consistent with the previously selected factor projections. If others in group disagreed with the consistency of the selected factor projection with those previously included in the framework, they were given the chance to suggest an alternative. However, if the participant who had originally selected the factor was not convinced by these arguments, s*he was free to stick with the original choice – provided s*he could justify the decision. Only one projection per factor was allowed to be used in each scenario framework. Once a factor projection had been used in one scenario framework, it could not be reused in another framework. Each participant was only allowed to pick one projection per scenario framework. Thus, each raw scenario framework was developed as part of a participatory and communitive process. The factor projections that were grouped together to form the resulting three raw scenario frameworks (blue, green and red) are colour coded in the table below.

No.	Title & description	Projection A	Projection B	Projection C	Projection D	Projection E
KU1	**Political will & support**: Political ecosystem, parties, parliament, & government. Excluding civil society. Political will = there is a general intent to support OAE. Political	Strong will & strong support	Strong political will & not much support	No political will & no support	No will & lots of political support (this would only happen if there was a sudden change/frequent	

	will is affected by lobbying, but not included in this factor. Political support = there is legislation & regulation in place to support OAE.				changes over time)	
KU2	**Economic incentive/profitability:** What is the price paid for OAE in relation to the cost? Pure technical costs. And one including MRV & potential damages (latter borne by the whole society? I.e. through subsidies for damage to fisheries).	**Not profitable:** Price is below technical costs: OAE would only be done if there were other incentives for doing so.	**Profitability** depends on who is paying: Price is between technical and overall cost (including MRV + compensation for damages). Profitability depends on who is playing for potential damages + MRV. If all of society is paying, it is ›profitable‹. If the companies have to pay themselves, it is not.	**Profitable:** Price is higher than technical costs plus MRV+ potential damages.	**Fluctuating profitability:** Average price is higher than technical +MRV, but **profitability is fluctuating or every hard to predict** (this would mean the average price over all would have to be higher to balance).	
KU3	**International cooperation and governance on climate**: Development of strength of international bodies.	**Powerful global cooperation and governance. Strengthened UN bodies.**	BAU, governance same as today: Ups and downs. Weak governance enforcement. Some global agreements (PA etc.)	Lack of global governance (no COPs etc), but regional or plurilateral cooperation formats. In collaboration with tariffs policy.	Zero cooperation. Dissolution of all relevant bodies. Direct geopolitical confrontation is possible under this projection.	
KU4	**Environmental side effects** on marine ecosystems. Positive/Negative/high low.	Positive side effects, high impact. (i.e. PH increase, counteracting acidification, increasing biomass)	Positive side effects, low impact	Negative side effects, low impact	Negative side effect, high impact: (i.e. Collapse of the food web, toxic substance release. Increase in toxic algae. Precipitation.)	
KU5	**Legal permissibility/legal allowance** Only research vs. implementation. Substances allowed – only purified alkaline materials vs. all possible materials allowed.	No OAE activity is legally allowed in the ocean. Only lab research for OAE.	Research can be done, but only with purified alkaline materials	Only research can be done in the ocean, but with all possible materials	Deployment can be done, but only with purified alkaline materials.	Deployment is legally allowed, with all possible materials
KU6	**Social perception** Local/coastal population vs. general population of	**»Not in my Germany«** (General &	**»Not in my backyard«** (Costal	**Local/costal acceptance** of	**General& coastal public agrees** on OAE	

	Germany's perception of OAE	coastal public against)	population rejects OAE, General public for)	OAE, general public against		

Table 3: Scenario frameworks

Creating pictures and histories of the future

In breakout groups, the participants then fleshed out these scenario frameworks. They first described a coherent descriptive »picture« of the future, based on the projections in their respective scenario frameworks. They then created a corresponding narrative »history«, or trajectory that could plausibly lead to the situations they describe. They did this by conducting a backcasting exercise and creating timelines of key events that lead to their described pictures of the future. They additionally developed a ›theory‹ of each of their futures, mapping the core dynamics and underlying structures driving change in each scenario, and narrative graphs that show the phases and turning points of the scenarios. The result of such a process was thus set of qualitative scenarios that not only provided a range of detailed pictures of the future, but also included a rich ›history‹ of each future – a pathway which describes the key technological, economic, political and social changes that would have to happen between today and that imagined future. In a final step, the participants were asked to reflect upon which aspects of each scenario they as a group considered to be (in)feasible or (un)desirable.

Reporting back and group feedback

In plenary, each group was then asked to present their coherent descriptive ›picture‹ of the future and the corresponding narrative ›history‹, or timeline of events that could plausibly lead to the situations they describe. In addition to asking questions to better understand the future worlds presented, the audience was invited to provide feedback based on two questions; (1) *What would you like to hear more about?* (2) *How could this scenario be made more plausible?*

3. Scenario descriptions

The following section contains details of the three scenarios developed at the workshop. The material presented for each scenario includes: (1) the scenario frameworks each breakout group used, (2) the timelines and tables they used to explain their imagined pathway from today to that plausible future, (4) the ›theory of the future‹ maps showing the core dynamics/underlying structures of each scenario, narrative graphs that show the phases and turning points of the scenarios, (6) the narrative scenario texts themselves.[3], (7) an overview of the OAE activity taking place in each of the imagined futures, and the tables showing which aspects of each scenario the respective group considered to be (in)feasible or (un)desirable.

[3] The narrative scenario description texts included here are based on the material developed during the workshop, incorporate suggestions raised during the plenary feedback round, and were shared with the original group members for feedback prior to publication in this report, but were compiled by the report author(s). The scenario descriptions presented here thus represent the **author(s)'** summary of and reflection on the workshop discussions and does not necessarily reflect the views of all participants.

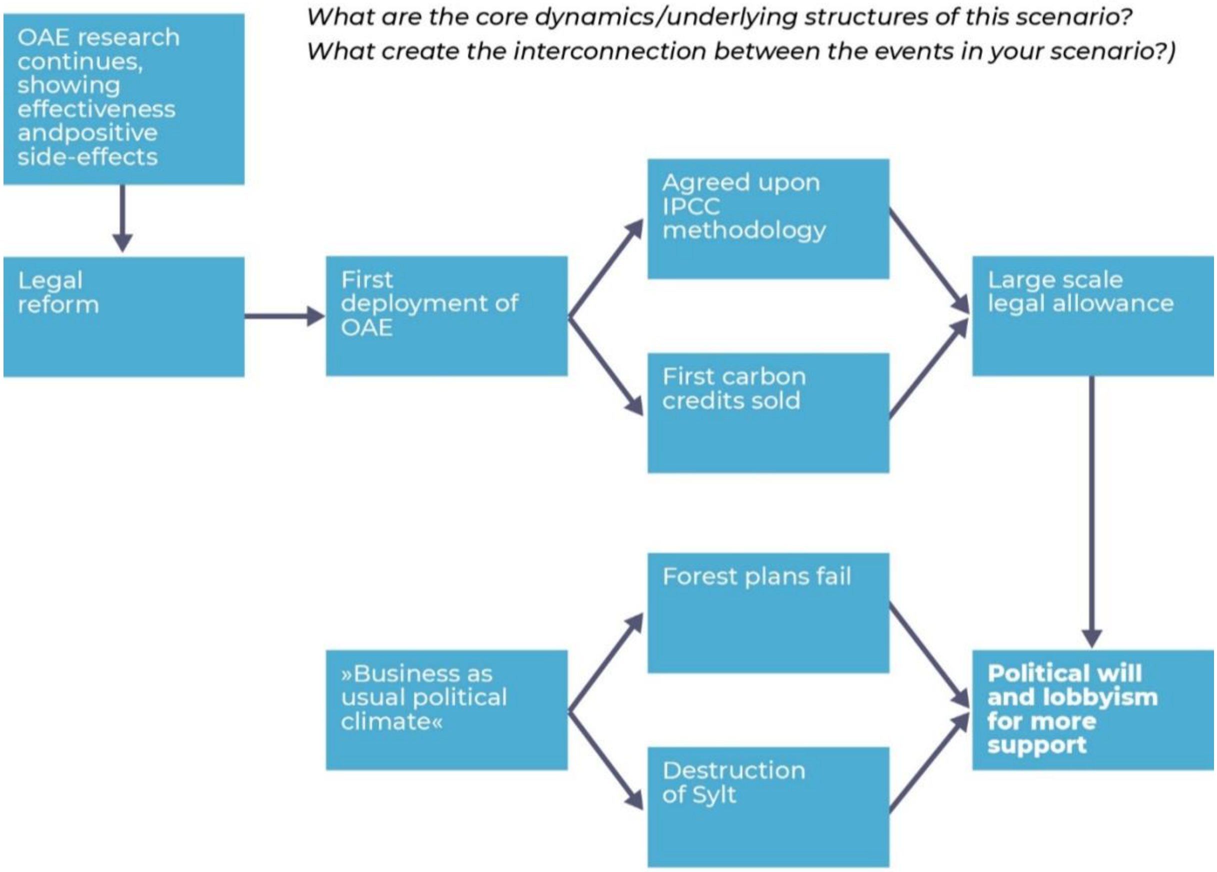
Blue Scenario: Enhance or fail – a cautious Germany shifts towards Ocean Alkalinity Enhancement

Overview

Political will and support for OAE	**Strong political will, not much political support**
Economic incentives	**Profitable**
International cooperation in climate mitigation	**Cooperation and governance as today**
Environmental side effects on marine ecosystems	**Positive side effects, high impact**
Legal allowance for activities and limitations on alkalinity substance	**Large-scale deployment is legally allowed, but only with pure alkalinity**
Social perception	**Only coastal population support OAE solutions**

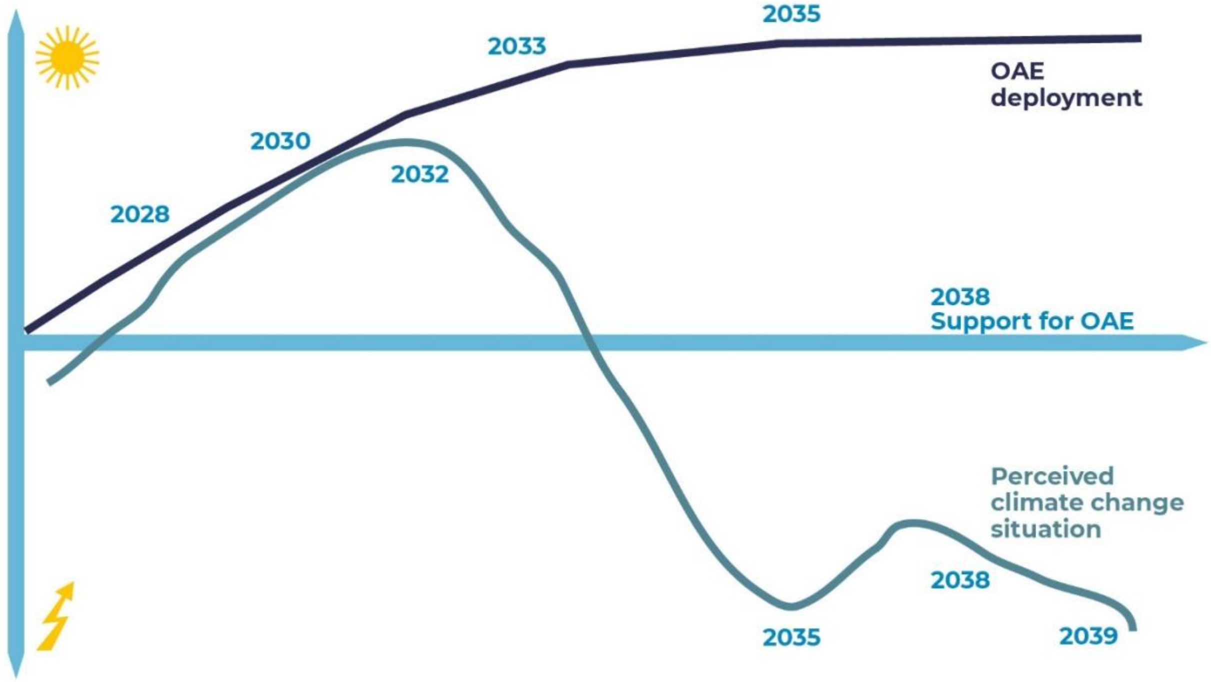
Theory of the future

(What drives/causes this scenario? What makes this scenario happen? What are the core dynamics/underlying structures of this scenario? What create the interconnection between the events in your scenario?)



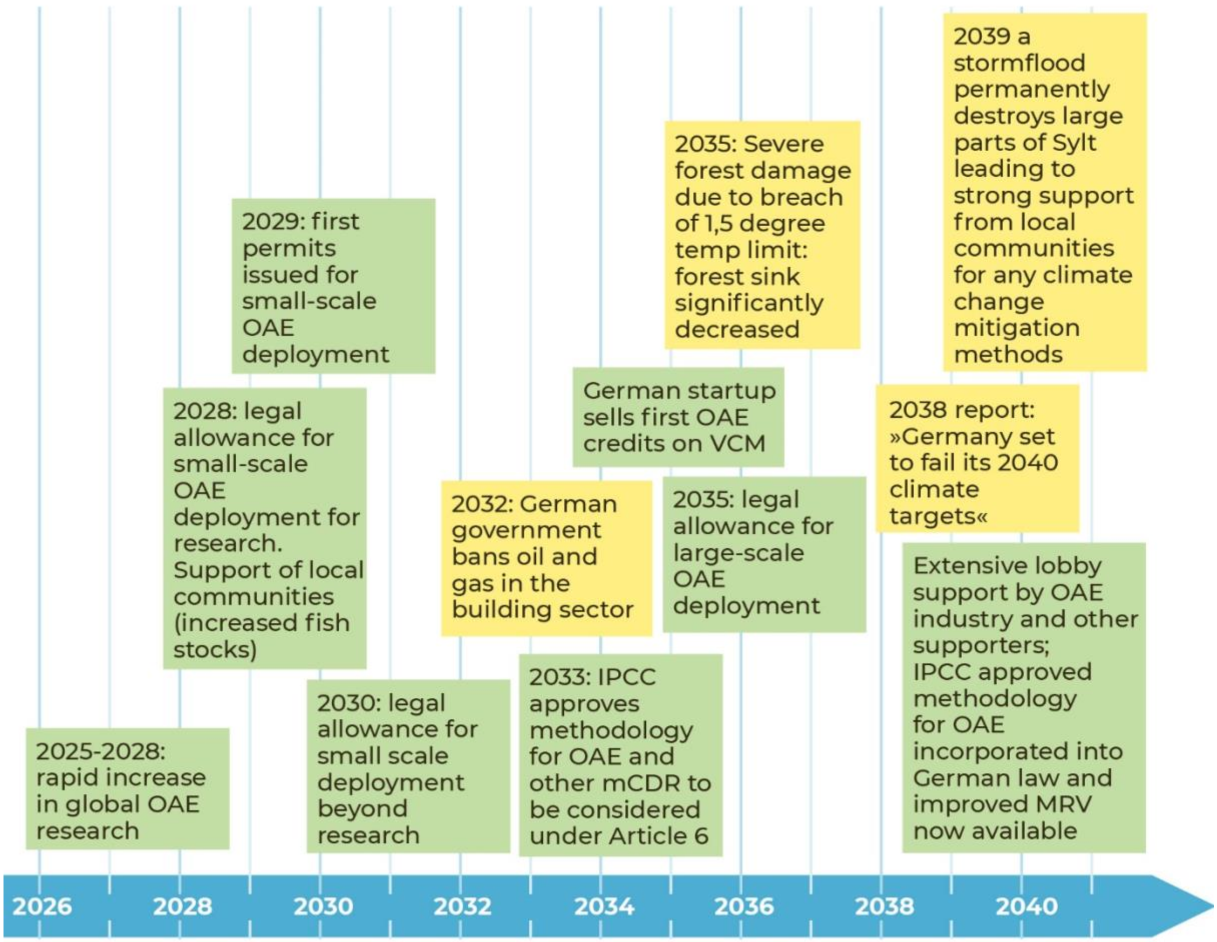
Narrative graph

(Phases and turning points and how they feel)



History of the Future

(What happened before? What are formative events? What are preconditions?)



History of the future

Period	Key developments	Dynamics driving change
2025 – 2028	Surge of international lab and mesocosm studies demonstrates that environmental risks of OAE can be managed with contaminant-free materials and careful dosing. Many research programmes pivot from proof-of-concept to small-scale coastal trials.	Research credibility grows as datasets are published under open-science mandates; early indications of co-benefits i. e. wastewater buffering, reduction of acidification stress on local organisms, increased productivity[4]) attract local coastal community interest.
2028 – 2030	German High Seas Dumping Act amended to permit small-scale OAE deployments using »pure alkaline materials« in German Exclusive Economic Zone, provided continuous monitoring and public disclosure. Voluntary Carbon Market (VCM) entities list first OAE credit methodologies.	Legal opening stems from alignment with precautionary principle: only low-risk minerals; real-time monitoring. Early entrants fund operations through VCM rather than subsidies.
2030 – 2035	IPCC approves OAE methodology for Article 6 reporting; EU signals intent to recognise durable ocean removals in post-2035 ETS. Domestic LULUCF sinks underperform due to compound drought and storm damage.	The relative attractiveness of marine CDR increases as terrestrial options falter. Start-ups form consortia with wastewater utilities, arguing shared infrastructure lowers cost.
2036 – 2038	Kilotonne-scale pilots verify net removal, positive environmental effects. Yet national deployment stalls: budget austerity and failed BECCS make policy makers wary; regulators await more robust MRV.	Political rhetoric supportive, but tangible support limited- »strong will, weak wallet.« Emerging OAE industry lobbies for clearer long-term signals.
2038	Germany misses its 2040 emissions-reduction trajectory; citing »insufficient negative-emissions portfolio.« Emergency Climate Package imposes higher carbon-price corridor and accelerates MRV standardisation.	Policy failure becomes a *pull* factor: cost of inaction now overtakes projected public expenditure on marine CDR.
2039	Winter storm cluster culminates in catastrophic breaching of Sylt's northern spit. Media framing pivots from abstract climate risk to visible coastal loss; coastal populations demand adaptive and restorative measures.	Symbolic loss influences public opinion; support for OAE spreads beyond communities that directly benefit economically.
2040 (present)	Regulatory certainty achieved: performance-based contracts allow scale-up to 10 kt CO_2 yr-1 nationally[5], still modest but no longer niche. Integrated OAE–wastewater plants become preferred early deployment model.	Technology poised to enter »ramp-up« phase: routine operations, professional workforce, expanding data records; societal debate beginning to shift from whether to deploy to how fast and where.

[4] A modelling study with the assumption that OAE will promote fish productivity: Sloterdijk et al. 2025.

It is projected that ocean acidification will become a problem in the Baltic Sea in the future. The benefit of OAE could be the counteracting effect in vulnerable coastal areas, which are often the breeding grounds for many species (Havenhand et al. 2019, Gustafsson et al. 2023).

[5] 10 kt CO_2 yr^{-1} for the regional Eckernförde Bight (Anschütz et al. 2025) or 3.2 Mt CO_2 yr^{-1} for the muddy regions in the Baltic Sea (Dale et al. 2024). Both are modelling results and should be considered with appropriate caution.

Blue Scenario Description: Enhance or fail – a cautious Germany shifts towards Ocean Alkalinity Enhancement

A crisp April morning unfolds across the port city of Kiel. From the observation deck of the ›Ocean-Climate Innovation Centre‹ one sees a narrow plume of finely milled and purified lime slurry being metered into the effluent stream of the adjacent wastewater plant before the mixture discharges into the fjord. Turquoise swirls mark the dispersion front; beneath them, small sub-surface Autonomous Underwater Vehicles (AUVs) flash green as they transmit real-time alkalinity data. On the quay, tonne-sized flexible containers of surplus alkaline material await shipment to similar pilot sites along the coast. Engineers in high-visibility jackets compare sensor read-outs with model projections; two social-science researchers interview dockworkers about job security and local perceptions of the project. After a decade of slow development, several start-ups in the coastal city are now leading the way in small-scale Ocean Alkalinity Enhancement (OAE) implementation.

Between 2025 and 2028, ocean-chemistry laboratories and coastal mesocosm stations around the world began to report that finely milled, contaminant-free alkaline minerals could raise seawater alkalinity and bind CO_2 without precipitating or creating significant environmental hazards. Following this positive news from international research, German institutes also began working more concertedly on OAE. Mindful of past controversies over marine geoengineering activities, they published all their data under open-science licences, and invested a lot of effort in researching potential environmental impacts. Stories of increased fishing yields associated with OAE testing in other parts of the world circulated through coastal newspapers and fishers' associations, turning what had been an academic curiosity into a subject of genuine local and economic interest.

The positive news about environmental impacts, along with growing public and commercial interest set the stage for a legislative change in late 2028. When updating the High Seas Dumping Act to reflect amendments to the London Protocol, the German parliament inserted a clause that legalised out-door OAE field-trails in German waters, but only if »pure alkaline materials« - alkaline material that has been purified to remove potentially harmful contaminants such as heavy metals - were used and all monitoring data were made available to the public. The narrow wording satisfied the precautionary principle while giving innovators a foothold.

International developments were also moving ahead. In the late 2020s, two voluntary carbon credit registries approved the first OAE methodologies, enabling start-ups to finance pilots entirely through credit sales. In many places, start-ups formed consortia with wastewater utilities, arguing that using existing pipes, pumps and staff could halve deployment costs compared with stand-alone ocean platforms or ship-based dispersal. In 2031, the IPCC adopted an accounting methodology that allowed OAE to be reported under Paris Agreement Article 6, and Brussels soon hinted that durable ocean removals would qualify for the post-2035 EU Emissions Trading System. At the same time, Germany's forests and biomass plantations for planned bioenergy came under increased stress from alternating drought and storm seasons, and shifted from being a net sink to net source. In addition to the loss of carbon removal potential in the Land Use, Land-Use Change, and Forestry (LULUCF) sector, these dynamics also reduced the availability of biomass for carbon capture and storage (BECCS) efforts. This further increased German interest in the role of the ocean as a carbon sink.

By mid-2037 several OAE projects had run kilotonne-scale pilot studies and, after painstaking monitoring efforts, demonstrated net CO_2 removal and net positive environmental effects. The scientific community applauded, yet German national rollout stalled. Burned by earlier misplaced BECCS optimism, the conservative incumbent government remained reluctant to invest more money in carbon dioxide removal (CDR) efforts. Regulators – wary of push-pack from environmental organisations who had previously opposed marine geoengineering in Germany – demanded the establishment of strict monitoring, reporting and verification and environmental impact assessment protocols before considering permitting large-scale OAE activities in German waters. Away from the coasts, public sentiment in Germany continued to swing between disinterest and rejection of the idea of intervening in marine environments, coupled with a general reluctance to support more government spending for other ›carbon management‹ approaches after massive investments in BECCS failed to achieve the desired results.

An extra incentive to undertake OAE arrived in 2038 when progress reports revealed that Germany would overshoot its 2040 climate target. Finally, nature supplied a final nudge. A cluster of winter storms in early 2039 breached Sylt's northern spit, flooding holiday homes and stripping entire dunes in less than two days. Drone footage of the destruction dominated the nightly news, and commentators who once debated the necessity of public spending on mitigation efforts now demanded use of every tool available »in the fight against dangerous climate change«. Public support for OAE spread among coastal towns; several coastal cities earmarked funds for alkalinity addition. In the spring of 2040, the technique no longer feels like a pipe-dream. Half a dozen integrated wastewater-OAE plants are operating along the German coast. Despite continuing ambivalence among the wider German public, coastal communities are largely supportive of OAE due to the promise of job opportunities and their perception of ›cleaner‹ waste water run-off into the ocean, as well the posited positive effects on ocean alkalinity reduction, fish production, and tourism. The increase in tourism is in part directly related to increased sport fishing opportunities, but also indirectly due to the resurgence of ›traditional fisheries‹ and associated re-branding of several coastal communities as ›traditional fishing villages‹ as a selling point for tourism. The scale of OAE activities remains modest in 2040, yet the debate has shifted. Editorials are no longer asking whether Ocean Alkalinity Enhancement belongs in the climate response toolbox; they are now debating how fast Germany can feasibly scale up its OAE activities without sacrificing the community-driven ethos that had made the approach desirable in the first place.

Overview of OAE activity taking place in 2040 in the blue scenario

Type of activity	Small-scale deployment of coastal ocean alkalinity enhancement
Time frame/duration/rate	2 - 3 years, multiple introductions
Implementation location/jurisdiction	German north (Baltic) coast, high energy area, coastal area with lots of tidal movement
Substance/matter being introduced (origin, form, amount. persistence etc.)	Lime/ calcium hydroxide. Finely milled, purified of additional substances, pre-mixed with sea water
Implementation scale (at introduction)	Half a dozen integrated wastewater-OAE plants (approx. 55,800 t $Ca(OH)_2$/yr for 6 plants, equivalent to ~159,000 t lime slurry at 35% solids; ~9,300 t $Ca(OH)_2$ per plant[6]
Actors implementing	Start-ups
Funding	Carbon credits on VCM
Delivery tech/infrastructure involved	Mining, Crushing/milling, purification, transport, pipes, pumps

[6] Numbers based on Hetlingen WWTP alkalinity addition, assuming all the discharged water is used = 7,845.5 µmol/L × 32×10^6 m³/yr = 2.51×10^8 mol alkalinity/yr. $Ca(OH)_2$ provides 2 mol alkalinity per mol, MW = 74 g/mol → 1.26×10^8 mol × 74 g/mol = 9,300 t $Ca(OH)_2$/plant/yr (≈ 26,500 t lime slurry at 35% solids). Scaled to 6 plants: ~55,800 t $Ca(OH)_2$/yr (~159,000 t slurry) (F.Liu, personal communication).

MRV tech/infrastructure involved	Gliders/Floats (upper water column) AUVs & & ROV (lower depths) for monitoring. Acoustic doppler current profiler (ADCP) Remote sensing (for surface level monitoring) Ship-based (underway measurements) monitoring more possible. Modeling and computing capability Quite large monitoring area due to dispersal, mixing etc. Dyes, tracers, coloring the water (smaller scale) to help monitor dispersal, to inform models
Removal potential/duration	Small (~53 kt CO_2/yr for 6 plants; est. based on η = 0.8 mol CO_2 per mol alkalinity added; ~0.007% of German GHG emissions)
Costs (›best guess‹) (including planning, implementation, MRV)	High.[7] The main cost drivers for WWTP-integrated OAE are: (1) mineral feedstock procurement and fine grinding[8]; (2) transport of alkaline material to the plant; (3) reactor installation and integration into existing wastewater infrastructure; and (4) MRV costs. Robust monitoring, reporting and verification of the actual CO_2 removal requires sensors, sampling, modelling and independent verification, which currently represents a substantial overhead for small-scale projects.
Anticipated ecological /environmental impacts (positive & negative)	Net positive environmental impacts. Despite some short-term negative impacts on plankton communities through reduced availability of CO_2 in the water column temporarily decreasing photosynthesis, the overall impacts are positive due to local reduction in acidification stress. Mussels' and other shell-fish stocks increase, also some positive knock-on impacts on other (commercially important) fish species due to increases in mesozooplankton abundance.[9]
Anticipated effects on other ocean uses in the area (fisheries, shipping, leisure etc.)	Positive, increase in tourism for sportfishing, increase in fish, shellfish stocks, no negative impacts on other ocean uses, apart from some need for coordination between fisheries/leisure boats so they hinder monitoring vehicles
Affected stakeholders	Local fisheries (positively affected by increase in fish & shellfish stocks), local residents involved in project planning, positively

[7] The closest real-world comparator is CREW Carbon, whose Wastewater Alkalinity Enhancement contract with Frontier implies ~$447/t CO_2 (71,878 t over 6 years for $32.1M; Frontier/CREW Carbon 2024, crewcarbon.com). This is consistent with current early-commercial OAE pricing (~$271–500/t; Frontier/Planetary 2025).

[8] Producing $Ca(OH)_2$ or limestone powder of sufficient particle size requires significant energy (~150–900 kWh/t; Eisaman et al. 2023)

[9] Local acidification stress reduction benefiting calcifiers is supported by carbonate chemistry principles (NASEM 2022). Experimental evidence for improved shell integrity in Mytilus edulis under OAE: Chen et al. 2026. Food web stability and zooplankton tolerance under moderate OAE: Sánchez et al. 2024.

	affected by job creation, waste water companies who are involved in deployment/implementation.
Regulatory landscape - jurisdictional responsibility, decision-making authority, permitting & monitoring processes, consultation requirements	Legally allowed under amended HSDA, local communities actively involved in project planning/design
Social context conditions such as economic and social vulnerabilities, economic structure, past experiences, environmental damage, and socio-cultural relevance of the marine environment	High socio-cultural relevance of marine environment, livelihoods connected to fisheries & tourism, negative experiences with environmental damage/climate damage.
Consultation/engagement/participation activities undertaken	Local communities are heavily involved project planning, implementation and monitoring.
Public perception of activity	Positive among local communities, but ambivalence and/or resistance among wider public in Germany. Local communities are heavily involved project planning, implementation and monitoring. Local fisheries (positively affected by increase in (shell) fish stocks), local residents involved in project planning, positively affected by job creation, waste water companies who are involved in deployment/implementation. This combines to lead positive local community perception of OAE. Away from the coasts, public sentiment in Germany continues to swing between disinterest and rejection of the idea of intervening in marine environments, coupled with a general reluctance to support more government spending for other ›carbon management‹ approaches after massive investments in BECCS failed to achieve the desired results.
Political contention about the activity	No contention, political will, but so far no political support (in terms of funding)

Desirable	Undesirable
Logical pathway to OAE implementation (research, legality, deployment)	Germany fails 2040 targets
Public support, political engagement, interest of private sector, involvement of various stakeholders	Sylt catastrophe
International cooperation still exists.	Carbon sink of forests is substantially decreased
Strong positive side-effects of OAE	Further delay in climate mitigation action (gap between science and action)
International & national climate targets are still being pursued	

Feasible	Infeasible
OAE legally feasible (large-scale deployment allowed)	Timing of legal allowances?
OAE technically feasible (start-ups have built commercial scale pilots)	Only good environmental effects; no bad environmental consequences
OAE economically feasible (OAE is profitable)	
OAE is feasible from social acceptance perspective	
Large scale support by local communities?	

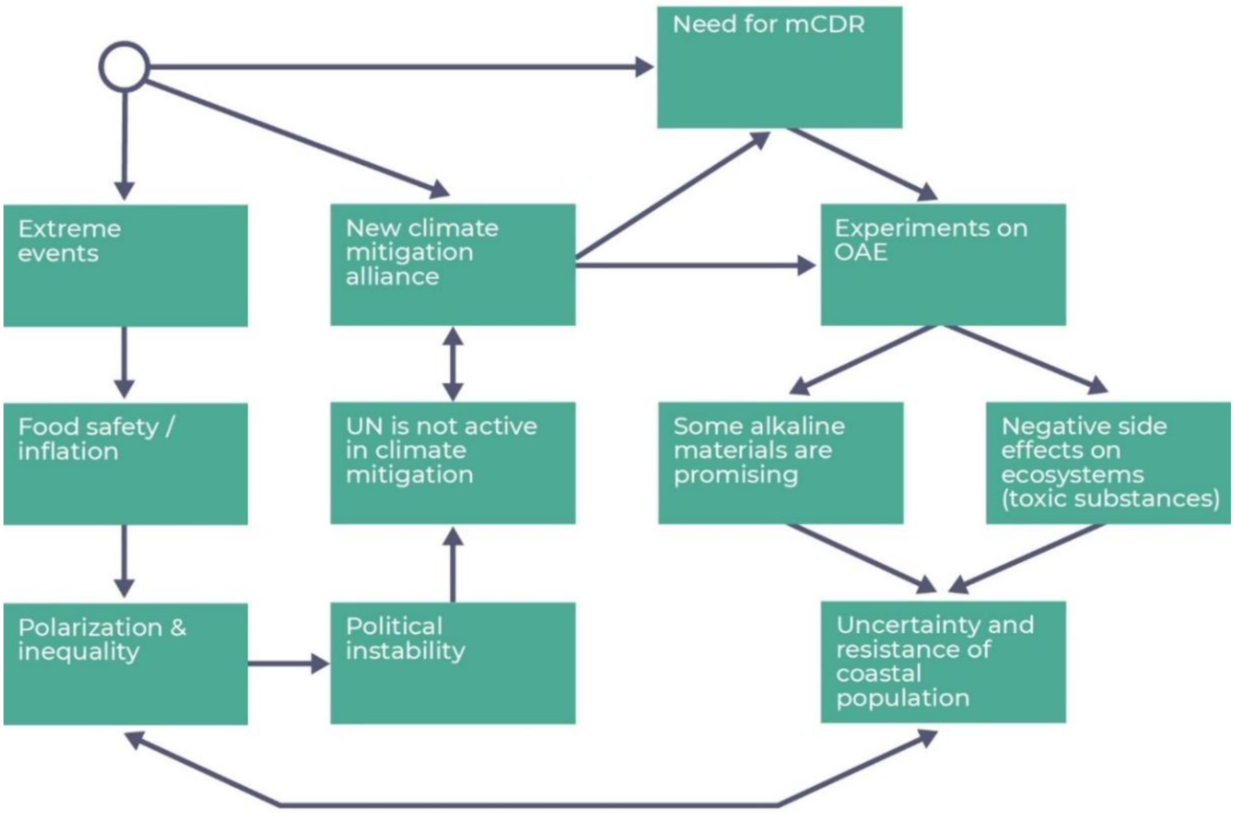
Green Scenario: OAE – A promising CDR method under fragmented governance

Overview

Political will and support for OAE	**Political will and support changing over time**
Economic incentives	**Potential profitability is fluctuating or hard to predict**
International cooperation in climate mitigation	**No global, but plurilateral cooperation and governance**
Environmental side effects on marine ecosystems	**Negative side effects, high impact**
Legal allowance for activities and limitations on alkalinity substance	**Only research is allowed, but all materials can be used**
Social perception	**»Not in my backyard«; Coastal population reject OAE**

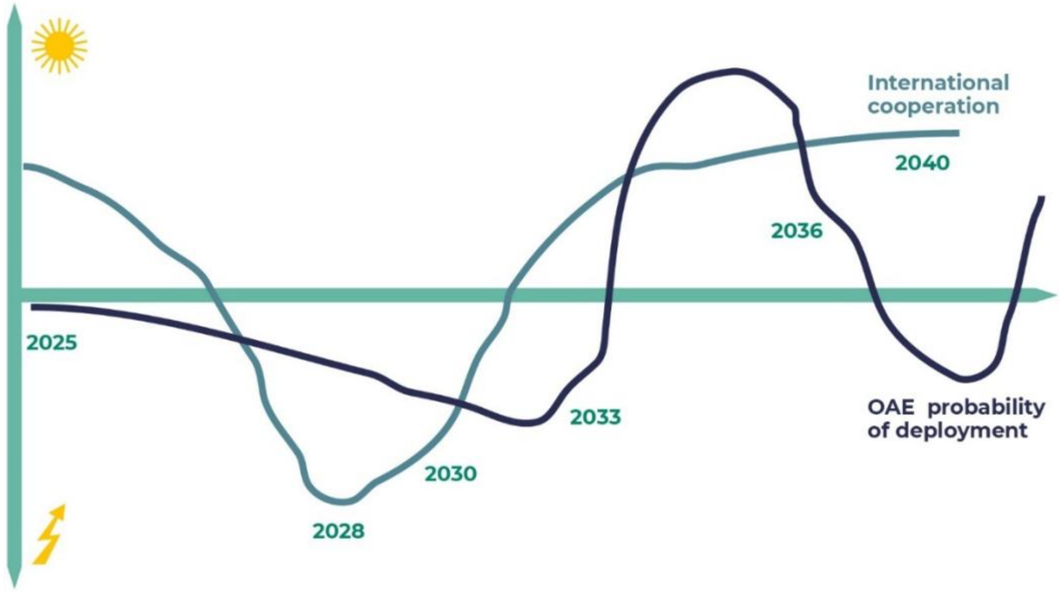
Theory of the future

(What drives/causes this scenario? What makes this scenario happen?
What are the core dynamics/underlying structures of this scenario?
What create the interconnection between the events in your scenario?)



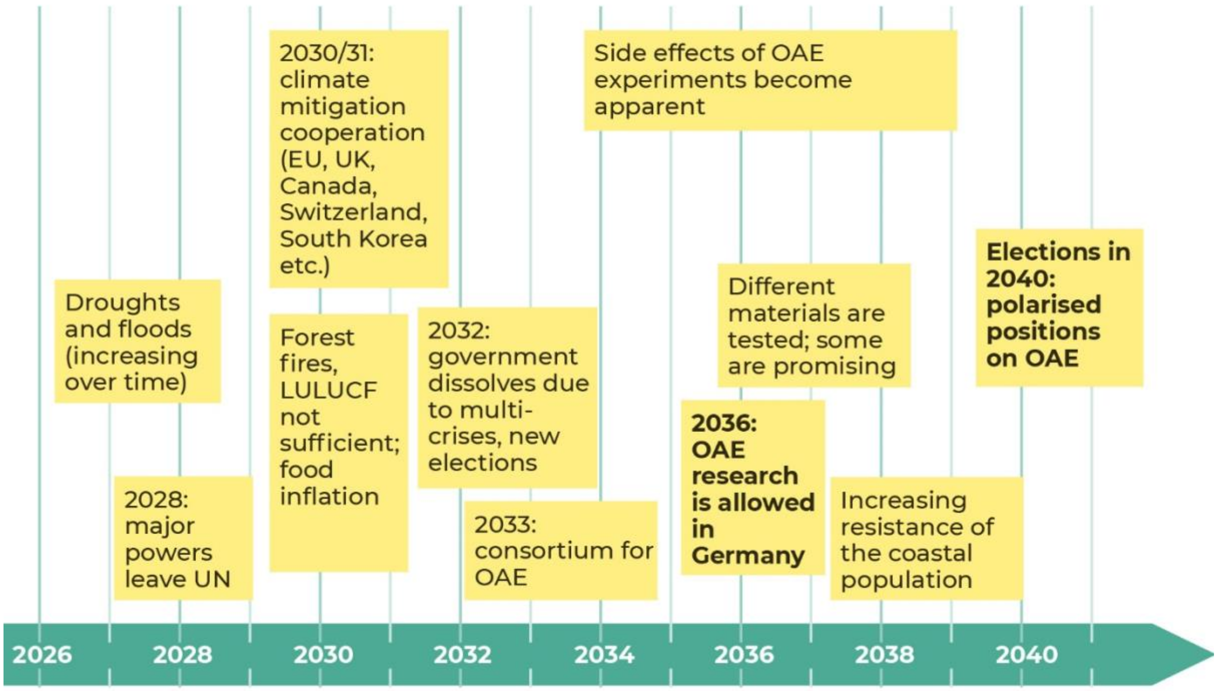
Narrative graph

(Phases and turning points and how they feel)



History of the Future

(What happened before? What are formative events? What are preconditions?)



History of the future

Period	Key Developments	Dynamics Driving Change
2025–2028	UNFCCC begins to lose relevance as major emitters withdraw. Germany allows small-scale OAE research under provisional guidelines.	Rising geopolitical tensions. Climate fatigue and nationalist resurgence in key countries. Push for CDR experimentation amid emissions overshoot.
2030–2035	EU-led »coalition of the willing« on climate emerges. LULUCF capacity collapses due to fires, droughts, and soil degradation.	Regionalism replaces global climate governance. Biophysical feedbacks intensify urgency. Domestic political polarisation deepens.
2036–2038	Initial OAE trials in German waters show negative ecosystem effects. NIMBY movements gain traction in coastal regions.	Lack of environmental safeguards. Heightened public sensitivity to ecological risks. Growing influence of local resistance movements.
2036–2038	Federal elections lead to rapid policy reversal on climate technologies. Protests against trials escalate. Investment in OAE declines.	Political instability from alternating coalitions. Influence of coastal constituencies grows.
2038	South Korea and UK begin pilot OAE deployments. Some German scientists publish positive results using purified alkaline materials.	International climate tech gains momentum. - Global CDR market incentives emerge. Research-practice gap persists in Germany.
2039	Germany misses revised EU mitigation targets. Public debate about OAE polarizes between interventionist and precautionary camps.	National credibility questioned in EU/climate coalition Civil society divided over ethics and equity of climate intervention.
2040 (present)	OAE remains stalled in Germany due to legal uncertainty. Some start-ups relocate to more permissive jurisdictions. Coastal opposition remains strong.	Ongoing regulatory vacuum. Low investor confidence. Fragmented public trust in institutions, private actors, and international processes. CDR and OAE in particular became a controversial topic for the next upcoming elections

Green Scenario Description: OAE – A promising CDR method under fragmented governance and fluctuating political conditions

It is the year 2040, and Germany – like much of the world – finds itself navigating turbulent waters of climate urgency, political instability, and contested technological innovation. The global climate governance architecture, once anchored by the United Nations Framework Convention on Climate Change (UNFCCC), has fragmented.

In its place, regional and plurilateral alliances have emerged – more flexible and adaptive, but also more volatile. Among them, a »coalition of the willing« including Germany, led by the EU, Canada, the UK, Switzerland, and South Korea, formed in the early 2030s, has taken on a leading role in advancing climate mitigation. These states, no longer bound by the need for global consensus, have pursued more ambitious climate goals, including the development of carbon import taxes and support for marine carbon dioxide removal (mCDR) technologies.

While this coalition facilitates innovation and action, it has also led to uneven burdens: Germany, for instance, has often shouldered a disproportionately high share of costs to support the joint activities of the new coalition, in addition to incurring costs due to the ongoing lack of international cooperation. This has further fueled domestic discontent and political pushback against spending on climate response options. Within Germany, the political debate around climate policy in general – and Ocean Alkalinity Enhancement (OAE) in particular – has become deeply polarised. Regulatory policy changes have stifled deployment, limiting Germany to the research of OAE.

A slow but decisive unravelling of global climate governance began in the late 2020s, when a string of major powers, most notably the United States, began withdrawing from multilateral climate commitments in 2027. This hollowed out the legitimacy and operational capacity of the UNFCCC, leading to a gradual withdrawal of both political capital and financial support for climate policy.

Initial small-scale field trials on OAE in Germany, as well as experiments being conducted in other countries with less prohibitive legislation concerning scientific field experiments from the mid-2030s onwards, revealed significant negative environmental externalities, including impacts on marine ecosystems and the marine food chain, impacting fisheries and tourism. These findings led to a sharp backlash from coastal communities, many of whom had already been economically impacted by declining fisheries and rising energy costs, as well as by the impacts of climate change. A strong »Not In My Backyard« (NIMBY) movement has since become a political force, effectively stalling any attempt to move beyond small-scale research.

The debate on OAE is occurring in the context of worsening climatic and socio-economic pressures. Germany's Land Use, Land Use-Change and Forestry (LULUCF) sector has been severely compromised. Forest fires, repeated droughts, and ecological degradation have diminished its carbon sequestration potential. Forests, moorlands and peatlands, once key carbon sinks, have become net sources. Starting around 2030, these cascading failures triggered intense national debate around the need to explore more aggressive or »engineered« climate solutions, including OAE.

In 2031, the search for more climate ambition culminated in a Coalition of the Willing, led by the EU, Canada, the UK, Switzerland, and South Korea, and aiming to lead in advancing climate mitigation. Without the need for global consensus, these states were able to reach an agreement among themselves on the joint development of carbon import taxes and support for marine carbon dioxide removal (mCDR) technologies.

Despite local NIMBYism, small-scale scientific research continued to expand also in Germany. In 2036, the newly elected Bundestag cleared the path to legalize large-scale OAE research. This step was encouraged by the publication of some newer studies that indicated reduced environmental side effects from purified alkaline substances and novel application techniques. But these findings had limited political traction. Public trust in science remained relatively intact, but trust in political institutions and private actors – especially start-ups seen as pursuing profit amid public risk – is markedly low in Germany. Debates over who should pay for potential damages, how to structure liability, and whether deployment would benefit some groups more than others have remained unresolved.

Meanwhile, other countries have pushed ahead. The United States ramped up its OAE activities in the early 2030s, leading to both technological breakthroughs and public controversies over ecological side effects. Japan and South Korea had, by 2038, moved toward commercial-scale deployment, coupling OAE with industrial innovation strategies and carbon market instruments. Some of these countries have now started to frame OAE not only as a mitigation tool but as a source of economic competitiveness in a carbon-constrained world: in addition to being a front-runner in OAE-tech-development, they are claiming economic competitiveness by selling carbon credits (at sometimes high prices) and counterbalancing some of their hard-to-abate industrial emissions, allowing them to continue to run these industries without large losses. These developments created tensions within Germany's political establishment: on the one hand, international deployment raised questions about Germany's strategic position in emerging climate tech markets; on the other hand, domestic resistance remained strong, particularly in regions already facing rising inequality.

The broader economic context in Germany in the lead up to 2040 is one of rising precarity. Inflation and food prices have climbed steadily due to climate-related crop failures and supply chain disruptions. The agricultural sector has suffered significantly, and public frustration is mounting. Some communities - particularly in coastal regions – oppose OAE on ecological and cultural grounds. Others, including drought-affected farmers and unemployed youth, increasingly demand stronger climate intervention, including through marine CDR. These cross-cutting grievances contribute to a polarised and unstable political environment, in which OAE functions less as a consensus solution and more as a symbol of broader political failures.

Political volatility in Germany has been ongoing since the early 2030s. After disagreements within the coalition on the issue of how to deal with the worsening impacts of climate change, in 2032 the federal government dissolved for the second time in a decade and federal elections were called a year earlier than expected. The following federal elections in 2036 once again brought tensions about climate response strategies to the fore, with parties holding opposing views on marine interventions for climate mitigation. In contrast to the previous government, the winning coalition was pro-OAE, but shifting political coalitions on the issue have been driven by voter frustration, climate-related shocks, and economic anxiety. As a result, no consistent regulatory framework for governing the risks and benefits of OAE has emerged. While the previous progressive government legally permitted research on OAE in line with development in other »coalition countries« – including the testing of a wide range of alkaline materials on a small scale – efforts to formalise risk governance, funding mechanisms, or upscaling deployment criteria have consistently stalled. As a result, no shared national consensus has emerged on how to fund OAE, regulate it, or integrate it into the broader mitigation strategy. Thus, while other developed countries have moved towards full-scale deployment in the late 2030s, developments in Germany have been much slower.

As of 2040, investment in OAE remains low in Germany, hindered by regulatory ambiguity, socio-political volatility, and unresolved distributive justice questions. Researchers and entrepreneurs express cautious optimism that more effective, less harmful materials can be developed, and that lessons from international OAE deployment might help stabilise public opinion. But for now, OAE in Germany exists in a state of suspended potential: neither fully rejected nor fully embraced, entangled in the wider story of a society struggling to govern the future under mounting climatic pressure. The upcoming elections, with clear and contradictory programs of the parties with regard to OAE, are likely to be a breakpoint/decisive for the further development of the technology in Germany.

Overview of OAE activity taking place in 2040 in green scenario

Type of activity	Small-scale OAE offshore
Time frame/duration/rate	Small-scale research in 2028-2036; large-scale research starting in 2036
Implementation location/jurisdiction	North Sea EEZ
Substance/matter being introduced (origin, form, amount. persistence etc.)	All types of alkaline substances
Implementation scale (at introduction)	Small: a few pilot-to-early-commercial projects at individual offshore sites. Sites 2–5, material: ~500–5,000 t calcite/site/yr, area: ~1–5 km²/site
Actors implementing	Start-ups
Funding	Entrepreneurial funding
Delivery tech/infrastructure involved	Ships, mining operations & transportation on land
MRV tech/infrastructure involved	Computational costs for ocean biogeochemical models, permanent monitoring stations, maintenance of data bases, ship time for targeted monitoring runs
Removal potential/duration	Small. ~5,000–50,000 t CO_2/yr total across 2–5 sites[10]
Costs (›best guess‹) (including planning, implementation, MRV)	High. Material and deployment costs for calcite-based offshore seafloor OAE estimated at 82–462 €/t CO_2.[11] Total costs including planning, ship time, monitoring stations, modelling and permitting likely substantially higher.[12] Lack of regulatory incentive structures/financial support.
Anticipated ecological /environmental impacts (positive & negative)	High negative impacts. Toxic heavy metal contamination; effects on fish and other marine wildlife; potential negative health effects for humans with high proportion of marine products for food supply.
Anticipated effects on other ocean uses in the area (fisheries, shipping, leisure etc.)	Fisheries and tourism (bird watching, sport-fishing, diving etc.) negatively affected due to heavy metal contamination having high negative impacts on fish and other marine wildlife.
Affected stakeholders	Coastal communities, fisheries
Regulatory landscape - jurisdictional responsibility, decision-making authority,	National law allows small-scale testing, but no regulatory governance, funding mechanisms, or upscaling deployment criteria etc.

[10] Estimate based on Anschütz et al. 2025 scaled to site area.

[11] Based on Fuhr et al. 2025

[12] Several hundred €/t CO_2; ~400–1.000 €/t. As comparison: 1) CREW Carbon (WWTP, different method, including MRV): ~$447/t, Planetary Technologies (coastal mineral OAE, inkl. MRV): ~$271/t

permitting & monitoring processes, consultation requirements	
Social context conditions such as economic and social vulnerabilities, economic structure, past experiences, environmental damage, and socio-cultural relevance of the marine environment	Economic precarity, increasing energy and food costs, negative ecosystem impacts of field trails have negative economic effects on coastal communities (fisheries & tourism) livelihoods.
Consultation/engagement/participation activities undertaken	Consultation/engagement with coastal communities before field trials in 2028-2030; broader engagement activities on (marine) CDR (also by scientists) with public in the 2030s
Public perception of activity	Negative ecosystem impacts of field trails have negative economic effects on coastal communities (fisheries & tourism) livelihoods. Coastal communities opposed. A strong »Not In My Backyard« (NIMBY) movement. Wider German population/civil society divided over ethics and equity of climate intervention. Climate-change-affected rural inland populations (farmers) increasingly demand stronger climate intervention action, especially in marine spaces which they see as less ›important‹ than land used for farming etc.
Political contention about the activity	Polarized between interventionist and precautionary camps.

Desirable	Undesirable
Effectiveness of OAE for climate mitigation	Negative side effects on ecosystems & health
Development of mitigation cooperation formats	Dissolution of the UN framework
Role of science for political decision-making	Polarization, lack of trust
	Extreme events (droughts, forest fires)

Feasible	Infeasible
Small-scale research on OAE	Legal feasibility of large-scale OAE deployment
Environment allows for OAE application	

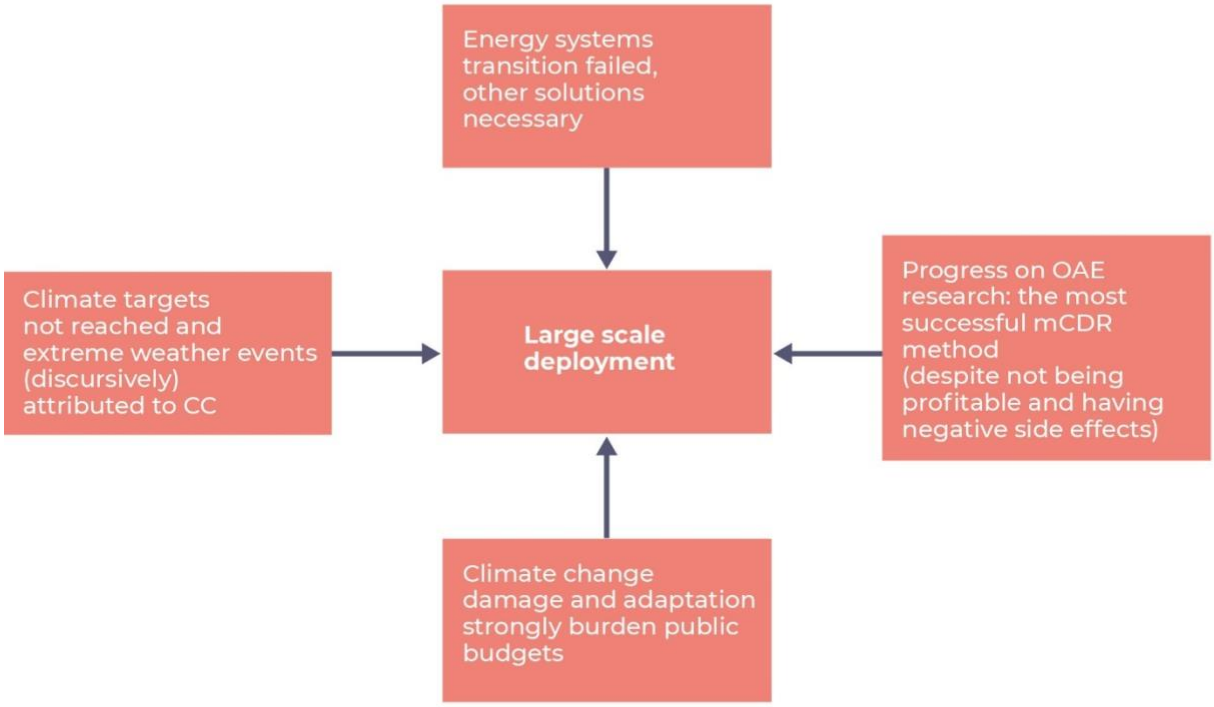
Red Scenario: OAE as an unpopular state-led emergency response

Overview

Political will and support for OAE	**Strong political will and strong political support**
Economic incentives	**Not profitable**
International cooperation in climate mitigation	**Powerful global cooperation & governance**
Environmental side effects on marine ecosystems	**Negative side effects, low impact**
Legal allowance for activities and limitations on alkalinity substance	**Full deployment is legally allowed with no restrictions**
Social perception	**»Not in my Germany«; General public rejects OAE**

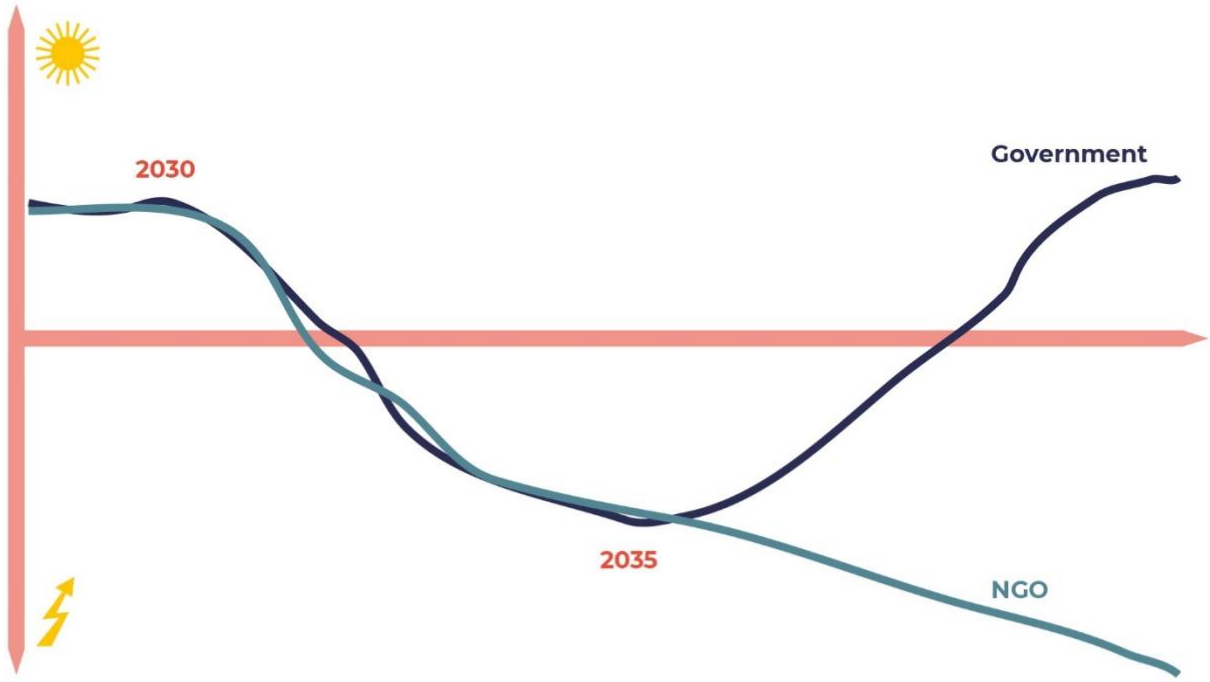
Theory of the future

(What drives/causes this scenario? What makes this scenario happen?
What are the core dynamics/underlying structures of this scenario?
What create the interconnection between the events in your scenario?)



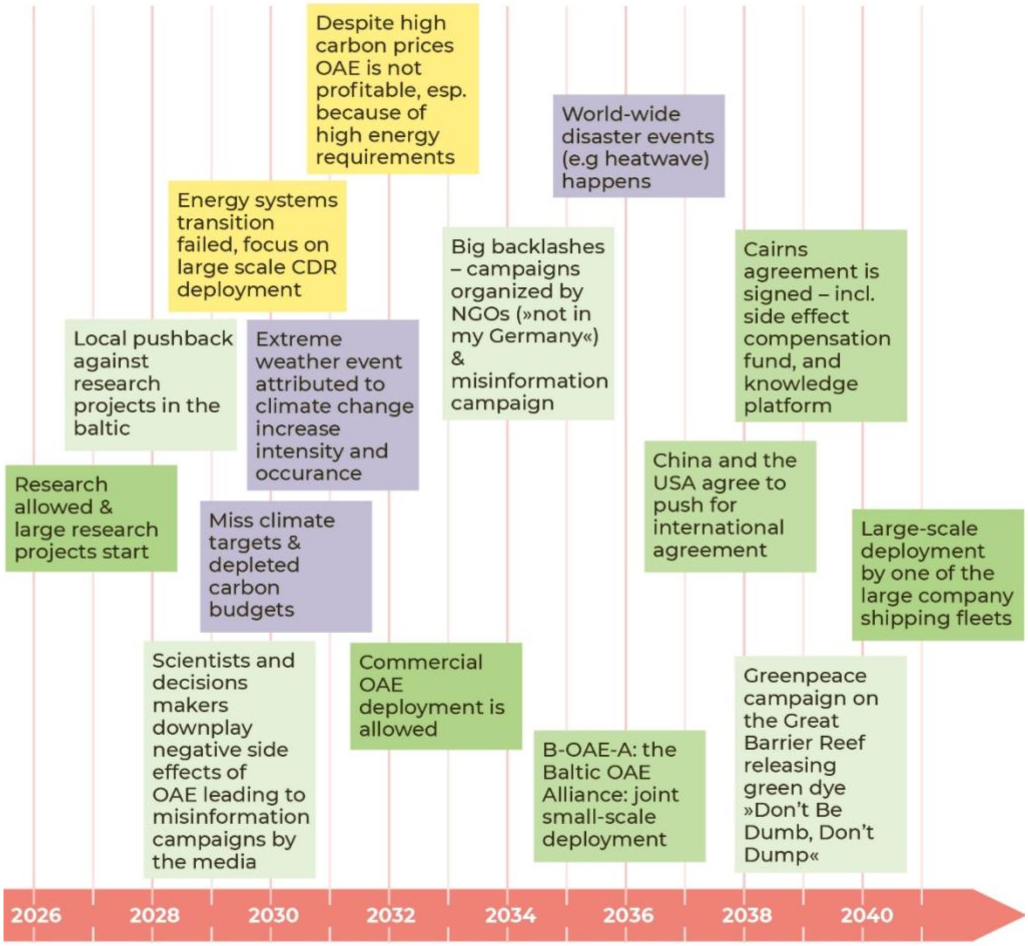
Narrative graph

(Phases and turning points and how they feel)



History of the Future

(What happened before? What are formative events? What are preconditions?)



History of the future

Period	Key Developments	Dynamics Driving Change
2025–2028	German government authorizes small-scale ocean alkalinity enhancement (OAE) research. Local opposition arises, especially in coastal Baltic areas. Media controversies link trials to marine mammal strandings; NGO campaigns intensify. Pilot deployments meet public resistance; protests escalate. International research offers cautiously optimistic findings; adverse effects deemed manageable.	Public opposition and misinformation Early governance gaps and lack of trust Technocratic imperative to proceed despite local resistance Incremental climate policy failure necessitating experimentation
2028–2030	Continued pilot testing and social contestation; gradual international research coordination.	Persistence of public skepticism Scientific uncertainty Weak carbon market incentives
2030–2035	Escalating climate disasters exceed response capacity. Baltic OAE Deployment Partnership formed by 9 governments. Carbon pricing remains politically unpopular; OAE lacks market viability. - Marine heatwaves decimate blue carbon ecosystems. Shift toward emergency framing of OAE.	Climate crisis and climate change mitigation failure Collapse of alternative CDR pathways Rise of centralized, top-down climate governance Framing of OAE as an emergency response
2036–2038	US, China, and EU initiate marine CDR coalition. Increased public R&D funding for OAE: COPXX yields the Adelaide Agreement, forming the International OAE Commission. Maersk announces government-supported fleet-based OAE deployment-ready retrofitting; others follow.	- Technocratic momentum and international alignment - Infrastructure integration, linking OAE to existing systems facilitates scale up (shipping & water treatment) - Strategic sidelining of public opposition - Creation of MRV and compensation frameworks
2038	Government-led testing expands; political momentum consolidates.	- Global governance support - Persistent public resistance politically marginalized
2039	UNFCCC classifies OAE as a strategic climate stabilization measure; substantial subsidies enacted.	- Technocratic imperative - Top-down international governance - Public consent bypassed in favor of perceived climatic/political necessity
2040 (present)	Large-scale OAE deployment in Baltic and North Atlantic regions planned as part of global deployment strategy; robust coordination among international partners; societal resistance persists.	- Centralized coordination and subsidies - Continuing erosion of public trust - Dominance of technocratic governance over participatory decision-making

Red Scenario Description: OAE as an unpopular state-led emergency response

By 2040, the world seems set to surpass the 2.5°C global warming threshold within the century. Mitigation efforts have consistently fallen short due to insufficient ambition, fragmented international coordination, and sluggish energy transitions that never scaled quickly or equitably enough. Climate impacts – heatwaves, droughts, storm surges – now routinely overwhelm infrastructure and public budgets in many countries around the world – including in Germany. In the context of this escalating crisis, Ocean Alkalinity Enhancement (OAE), has shifted from a niche idea for carbon removal to a political necessity.

OAE, long side-lined due to ecological risks, energy intensity, and high costs, is now at the centre of international discussions on climate response strategies. It is neither profitable nor publicly accepted. Nevertheless, it has become a cornerstone of late-stage climate governance: not because it is ideal, but because other options – particularly ecosystem-based CDR approaches such as afforestation and blue carbon enhancement – have failed or been reversed due to climate impacts. A lack of other options, more than confidence, is now driving the deployment of other types of carbon removal.

In 2026, the German government authorized small-scale OAE research in the North and Baltic Seas. Despite its limited scope, local NGOs and media organizations picked up the story and started voicing skepticism and fear of adverse effects. Pilot deployments thus experienced strong local opposition. In 2027, newspaper headlines attributing marine mammal strandings to OAE further inflamed public push-back. These incidents, although scientifically unrelated, became emotionally powerful vehicles for mobilising anti-OAE protests. Despite repeated efforts by scientific bodies to clarify the evidence, the reputational damage was done.

At the turn of the decade, OAE was publicly contested. At the same time, sluggish growth in other mitigation efforts increased the necessity for carbon dioxide removal. This justified the German government's decision to join the »Baltic OAE Deployment Partnership« – a regional collaboration between the nine Baltic coastal states. However, this move by the government also triggered widespread public backlash. The discrepancy between public and government positions on OAE would become a constituent feature of German climate policies in the first half of the 2030s. Long known for its strong environmental movement, Germany found itself divided between climate urgency and ecological precaution. Civil society and environmental NGOs accused the government of repeating the mistakes of the nuclear era: top-down, high-tech solutions with poorly understood risks. Slogans such as »Not in my Germany« and »Don't experiment with our ocean« dominated public protests. A growing number of activists drew parallels to previous techno-political failures and fuelled mistrust in both the science and the governance structures surrounding OAE.

In 2034, the German debate was shaken up by environmental catastrophe. An unparalleled global marine heatwave hit, decimating kelp forests, seagrass meadows and other blue carbon sinks. In combination with frequent forest fires, this turned large portions of countries' natural carbon sinks into sources. In response, the German government shifted its communication on OAE, which it henceforth declared indispensable for the fight against climate change. The more the German government pushed for OAE, the more staunch public opposition became.

Internationally, however, momentum was building. In 2037, at COP42 an agreement was signed, establishing a new International OAE Coalition (IOC) led by the United States, China, and the European Union. The agreement formalized a global OAE governance regime, including: a common Measurement, Reporting, Verification (MRV) framework to ensure consistent monitoring of both carbon removal and ecological side effects; A compensation fund for affected marine ecosystems and fisheries; An open-access knowledge-sharing database for OAE deployment protocols and technical best practices.

The Coalition represented a clear turn toward top-down internationalism, where climate emergency trumps participatory decision-making. Within this structure, from 2037 onward, states have begun to take on the financial burden of CDR through direct public funding, new climate levies, and sector-specific carbon taxes, as carbon markets fail to produce adequate price signals. OAE remains economically unattractive due to high capital costs (especially alkaline slurry production and transport), unresolved energy requirements, and limited infrastructure compatibility. States' willingness to foot the bill, however, changed; for the first time, large-scale deployment was planned that would approximate the levels needed for significant mitigation.

The energy transition, while not entirely failed, has been significantly delayed in Germany. Renewables are continuing to expand in 2040, but cannot meet the demand of decarbonizing the energy system and additionally powering energy-intensive CDR methods. Although some OAE systems have been retrofitted to run on excess renewables or are co-located with sewage plants and desalination facilities, much of the early deployment is powered by a still-partially fossil-based grid. This compromises the net removal efficiency of OAE and attracts further criticism.

By 2039, German shipping giant Maersk (headquartered in Denmark but influential in German politics) retrofitted its entire fleet with onboard OAE dispersal systems. While this signalled private sector engagement, it is largely driven by political pressure and regulatory incentives rather than economic rationale. Shipping and wastewater treatment are increasingly targeted as high-volume sectors for OAE scale-up, but public confidence in their safety remains low.

In 2040, scientists are divided on the efficacy and safety of OAE. While some point to improved energy efficiency and the new impetus behind the energy transition, better dispersal models, and increasingly precise impact forecasting tools, others raise alarm about biodiversity shifts, nutrient imbalances, and the unknown effects of long-term pH-changes. In particular, the potential toxic effects of introducing alkaline materials remain a grey zone, and side effects such as shifts in dominant species of primary production continue to spark concern. Nonetheless, mainstream scientific institutions increasingly frame these risks as acceptable trade-offs in light of the worsening climate crisis.

Thus, the OAE push is less a reflection of scientific consensus or public will than a product of »promissory politics« – the belief that future technological optimization and energy decarbonization will eventually justify today's interventions. Governments have adopted a gamble: deploy now, optimize later. OAE has become a geopolitical bargaining chip, and a signal of Germany's commitment to international climate action. The decision to proceed with large-scale OAE – despite its costs, risks, and public opposition – is representative of a broader shift in global climate governance: from precautionary, consensus-based planning to emergency-driven, state-led action.

Overview of OAE activity taking place in 2040 in red scenario

Type of activity	Large-scale OAE offshore (planned to start)
Time frame/duration/rate	Decadal
Implementation location/jurisdiction	Open ocean (Atlantic) & EEZs/territorial seas (Baltic)
Substance/matter being introduced (origin, form, amount. persistence etc.)	Lime slurry
Implementation scale (at introduction)	Large scale, ~1.8–17.9 Mt limestone/yr and ~1,500–15,500 km² dispersal area[13]

[13] Scaled from Yao et al. (2025): achieving 10 Mt CO_2/yr removal via ship-based ocean liming in the German North Sea would require ~17.9 Mt limestone/yr and a sea area of ~15,500 km². In this scenario (planned deployment, not yet at full scale in 2040), a fraction of this: ~1–10 Mt CO_2/yr target

Actors implementing	Governments, with private shipping companies
Funding	Governments/tax payers
Delivery tech/infrastructure involved	Retro-fitted ships for dispersal, sewage plants for OAE slurry production
MRV tech/infrastructure involved	Tracking of ship-based dispersal effects. Modelling based and (unmanned) sampling vessels.
Removal potential/duration	High, assuming continuous dispersal. Target: ~1–10 Mt CO_2/yr. CO_2 uptake efficiency around 0.8 mol CO_2 uptake per mol alkalinity addition. But not all the absorbed CO_2 will stay in the ocean long periods since only a small proportion of the CO_2 can be efficiently transported to the deep ocean.
Costs (›best guess‹) (including planning, implementation, MRV)	High. Estimated costs for large-scale ship-based ocean liming ($Ca(OH)_2$ dispersal): ~$70–295/t CO_2 depending on energy source and whether CCS for calcination CO_2 is included. At programme scale of 1–10 Mt CO_2/yr, total costs would be in the range of €0.1–3 billion/yr.[14]
Anticipated ecological /environmental impacts (positive & negative)	Negative, but relatively low impacts: Some nutrient imbalances are being observed. The effects of long-term pH changes are unknown. Side effects such as some shifts in dominant species of primary production continue to spark concern. Nonetheless, mainstream scientific institutions increasingly frame these impacts as relatively low, and as acceptable trade-offs in light of the worsening climate crisis.
Anticipated effects on other ocean uses in the area (fisheries, shipping, leisure etc.)	Fisheries negatively affected by shifts in primary production species, but impacts remain minor. Shipping industry benefits from direct government subsidization for retrofitting of ships for dispersal of alkaline materials
Affected stakeholders	Shipping companies, public tax payers
Regulatory landscape - jurisdictional responsibility, decision-making authority, permitting & monitoring processes, consultation requirements	OAE allowed under German and international law, MRV and compensation mechanisms in place; there is an open-access knowledge-sharing database for OAE deployment protocols and technical best practices.
Social context conditions such as economic and social vulnerabilities, economic structure, past experiences, environmental damage, and socio-cultural relevance of the marine environment	High energy costs, taxes, climate impacts in Germany
Consultation/engagement/participation activities undertaken	None

[14] Cost range based on Renforth et al. 2013 and Kowalczyk et al. 2024, covering limestone extraction, calcination, hydration and ship dispersal. Lower end (~$70–160/t) assumes fossil-fuelled calcination with CCS; upper end (~$130–295/t) assumes fully decarbonised energy. Without CCS for the calcination step, net CO_2 removal drops significantly.

Public perception of activity	Very negative perception of OAE among both local and general publics. Local NGOs and media organizations picked up the issue early and started voicing skepticism and fear of adverse effects. Pilot deployments of OAE experienced strong local opposition. In 2027, newspaper headlines attributing marine mammal stranding to OAE further inflamed public push-back. These incidents, although scientifically unrelated, became emotionally powerful vehicles for mobilizing anti-OAE protests. Despite repeated efforts by scientific bodies to clarify the evidence, the reputational damage was done. There is generally a feeling that public consent has been bypassed in favor of perceived climatic/political urgency to act. The discrepancy between public and government positions on OAE is very evident. Long known for its strong environmental movement, Germany has now found itself divided between climate urgency and ecological precaution. Civil society and environmental NGOs accuse the government of repeating the mistakes of the nuclear era: top-down, high-tech solutions with poorly understood risks. Slogans such as »Not in my Germany« and »Don't experiment with our ocean« dominated public protests.
Political contention about the activity	Public pushback not reflected in political sphere – strong political will and support

Desirable	Undesirable
International coalition of governments is coming together to fight climate change	German public opposes governmental enforcement of OAE
OAE is proven to be effective at capturing CO_2	Negative side-effects of OAE outweigh positive side-effects
Private companies show interest in participating in climate mitigation (towards a polluter removes?)	Unprofitable
Transparent sharing of knowledge and best practices globally	Misinformation campaigns
Distributional justice through the compensation funds	Intransparent communication of side-effects by the research community

Feasible	Infeasible
OAE is proven to be effective at capturing CO_2	Emission reduction seems politically undoable, climate targets not reached
OAE infrastructure is developed for small-scale deployment	OAE negative ecological effect can not be solved
OAE is taking place despite it being unprofitable	OAE can not rely on renewable energy
MRV standards are set	

4. Comparative reflections and conclusions

When asked to reflect on their key take-aways from the scenario workshop, the participants highlighted how much it seemed that **wider international political dynamics** might shape if, when, and how OAE is developed and implemented by Germany: whether through multilateral coalitions (Blue scenario), under conditions of fragmented governance (Green scenario), or via top-down global agreements (Red scenario), the international context shaped both the feasibility and perceived desirability of OAE in Germany. In addition, the participants observed that the scenario dynamics showed that action on OAE often happened after a **major crisis** (i.e., significant climate impacts, missed emissions targets, climate-driven economic losses) with these kinds of events kick-starting or driving decisions on OAE in the scenarios. This raised questions about whether current political systems can or will act early enough on climate change more generally, without such external pressure. This also led to discussion of the risks that can arise if decisions on OAE were to be taken under crisis conditions rather than through anticipatory and participatory processes.

A theme running through all the scenarios was the **relationship between public perception, political will, and scientific evidence**. In all three scenarios, scientific evidence alone did not drive decision-making on OAE; equity considerations, and (public & political) perceptions of environmental risk also played key roles in shaping OAE trajectories in the scenarios. This prompted reflection on whether the workshop group (which was primarily made up of academics) had a tendency to overestimate the influence scientific evidence might have on real-world decision-making around OAE. Participants also noted that although civil society was seen as playing key role in several of the scenarios, civil society voices - especially those of NGOs - were largely absent in the scenario development group, leaving open questions about who shapes (or should shape) discussions and decisions around OAE.

The workshop also highlighted the **limits and opportunities of this sort of foresight scenario** development methodology itself. Participants agreed that these types of scenarios can help structure thinking about a range of plausible futures, but even so, they only ever capture a sub-set of possible futures, and are only as diverse as the group developing them. In addition to having diverse perspectives, disciplines and expertise involved, making the assumptions that feed into the scenario development process explicit was seen as essential, since unclear or hidden assumptions can distort how the scenarios are interpreted. Designing complex but still plausible scenarios that truly integrate ecological impacts, political dynamics, and social concerns was seen as both necessary and challenging. Finally, the process reminded participants of the value of collaboration across disciplines and perspectives when thinking through plausible future developments, even when it can be challenging.

One example of the **challenges of such interdisciplinary communication** that arose during the scenario development process was a discussion about the role of the profitability of OAE in driving (political) action. For those workshop participants used to operating under the assumption that rational actors apply cost-benefit calculations and only take action if the (financial) benefits outweigh the costs, the Red Scenario (in which governments are supportive of OAE implementation despite the fact that it was not profitable), seemed rather implausible. However, to those who have a background in tracing historical (climate) politics and policy developments, and assume that actors sometimes have inherently political motives for making (climate) policy decisions, the scenario in which OAE became a political bargaining chip, and a signal of Germany’s commitment to international climate action seemed quite plausible. This discussion once again made it clear that this type of participatory scenario development methodology is very useful for making the (often implicit) assumptions that shape the scenarios explicit, and for reflecting upon how changing key assumptions could lead to alternative scenario outcomes.

This report has outlined the process and key insights from a single participatory foresight exercise. It is important to emphasize that the OAE scenarios developed during these processes are **exploratory** in nature. They are designed as **thought experiments** to stimulate structured dialogue about possible OAE futures in the German context among a specific group of participants. The resulting scenarios are context-specific and **should not be interpreted as forecasts of probable futures**. Instead, they serve as a starting point for further forward-looking discussions and highlight the value of such approaches for examining the complexity of OAE development pathways.

As the reflections in this report illustrate, such participatory foresight processes can be a valuable means to (1) expand our understanding of possible OAE developments and (2) encourage more critical reflection on the assumptions shaping how we think about OAE and wider climate futures.

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Annex

Anonymized participant list

No.	Affiliation	Expertise
1	Academia	Integrated assessment modelling
2	Academia	Integrated assessment modelling
3	Academia	Earth System Modelling
4	Academia	Law
5	Academia	Economic modelling
6	Academia	CDR Policy & Politics/IPCC
7	Academia	CDR Policy & Politics
8	Academia	CDR Policy & Politics
9	Academia	Modelling of the North Sea
10	Academia	Ocean biogeochemistry
11	Academia	Ocean biogeochemistry
	Academia	Ocean biogeochemistry
12	Administration/regulatory bodies	Nature protection/regulation of human activities
13	Administration/regulatory bodies	Nature protection/regulation of human activities
14	Administration/regulatory bodies	Marine spatial planning
15	Administration/regulatory bodies	Law/German Long Term Negative Emissions Strategy
16	Civil society	Nature/marine protection

List of Influential Factors

Foresight Intelligence

List of Influential Factors

Ocean Alkalinity Enhancement Scenarios for Germany 2040

1. Geopolitical tensions (high or low?)
2. International cooperation on global challenges in general and climate change in particular
3. Collaboration between neighboring countries (e.g. Germany, Norway) (Will the neighboring counties come up with some collaborative strategies to do the OAE?)
4. Carbon targets of Germany and EU and structure of targets and climate policy commitments (how much CDR and OAE will be allowed and needed under certain climate strategies?)
5. Economic incentives and political economy of OAE and integration in carbon markets or EU ETS
6. Is there an integrated (international) governance framework for negative emissions in general and OAE in particular?
7. OAE implementation in other countries (EU, US, CHN, neighbouring countries of GER)
8. Political will and support for OAE in the CDR portfolio
9. German government's stance of science, environment and climate issues (high or low on the agenda? Level of science ignorance in government? Polarized or not?)
10. Support or conflicting interests of stakeholders (fishing industry e.g.)
11. Severity of expected and unintended environmental side effects and impacts on marine, coastal, and other ecosystems (were the impacts strong or weak? Anticipated or not?)
12. Health side-effects (Will there be any identified human health side-effects or not?)
13. Existence of a comprehensive, transparent site specific environmental risk assessment
14. OAE research and pilot projects (Did it or did it not cause any environmental damages? Did they help to reduce side effects?)
15. Geographic suitability (which waters are suitable for OAE in 2040 considering climate change stress?)
16. From mitigation-only to dual-purpose climate solutions (Carbon removal and ocean acidification buffering) [6]
17. Effectiveness of OAE (small or large effect on reducing GHG emissions?)
18. Emission pathway and global warming
19. Life cycle assessments and efficiency of the option in a national setting (How can LCA guide strategic decisions to maximize net climate benefits while minimizing ecological and societal costs) [32]
20. Social perception, acceptance of, and support for carbon negative technologies and OAE sites or projects

OAE Scenarios for Germany 2040

OAE 2040 Factor Assessment

No	Factor	Uncertainty	Impact	Varianz-Score
1	Geopolitical tensions (high or low?)	3,610	2,405	6,86
2	International cooperation on global challenges in general and climate change in particular	3,271	2,557	10,69
3	Collaboration between neighboring countries (e.g. Germany, Norway) (Will the neighboring counties come up with some collaborative strategies to do the OAE?)	2,213	2,540	17,89
4	Carbon targets of Germany and EU and structure of targets and climate policy commitments (how much CDR and OAE will be allowed and needed under certain climate strategies?)	2,467	3,072	8,09
5	**Economic incentives and political economy of OAE and integration in carbon markets or EU ETS**	**2,800**	**2,808**	12,82
6	**Is there an integrated (international) governance framework for negative emissions in general and OAE in particular?**	**3,020**	**2,411**	15,56
7	OAE implementation in other countries (EU, US, CHN, neighbouring countries of GER)	3,015	2,137	10,19
8	Political will and support for OAE in the CDR portfolio	3,349	3,406	5,03
9	German government's stance of science, environment and climate issues (high or low on the agenda? Level of science ignorance in government? Polarized or not?)	2,344	2,489	9,39
10	**Support or conflicting interests of stakeholders (fishing industry e.g.)**	**2,605**	**2,674**	14,87
11	Severity of expected and unintended environmental side effects and impacts on marine, coastal, and other ecosystems (were the impacts strong or weak? Anticipated or not?)	3,003	2,957	14,68
12	Health side-effects (Will there be any identified human health side-effects or not?)	1,946	2,419	10,91
13	Existence of a comprehensive, transparent site specific environmental risk assessment	2,210	2,419	13,89
14	OAE research and pilot projects (Did it or did it not cause any environmental damages? Did they help to reduce side effects?)	2,212	2,605	6,55
15	Geographic suitability (which waters are suitable for OAE in 2040 considering climate change stress?)	1,818	2,224	7,82
16	From mitigation-only to dual-purpose climate solutions (Carbon removal and ocean acidification buffering) [6]	2,081	1,941	5,44
17	**Effectiveness of OAE (small or large effect on reducing GHG emissions?)**	**2,274**	**2,953**	**11,54**
18	**Emission pathway and global warming**	**2,414**	**2,535**	**14,98**
19	Life cycle assessments and efficiency of the option in a national setting (How can LCA guide strategic decisions to maximize net climate benefits while minimizing ecological and societal costs) [32]	1,888	1,812	5,99
20	**Social perception, acceptance of, and support for carbon negative technologies and OAE sites or projects**	**2,871**	**2,807**	**18,40**
21	Competing uses of the ocean and competing societal interests such as housing, space for food, tourism, sites with cultural, historical significance etc. (intense or low?)	2,083	2,341	9,08
22	Communication (also through media) and transparency of OAE research and projects to the public	2,344	2,412	16,85
23	German public perception of progress in (global) emissions reduction	2,291	2,215	17,19
24	Technical feasibility, maturity, and scalability of OAE application methods and availability of respective (transport) infrastructure	2,337	2,686	7,91
25	CDR potential (How many tons of CO2 can be removed with a plausible material input and space?)	2,471	2,681	12,94
26	Energy requirements of OAE and availability of renewable energy in Germany	1,672	2,681	6,56
27	Co-benefits and penalizing	2,614	2,083	5,78
28	Supply chain innovation (Will the use of industrial by-products (e.g. steel slag, cement waste) be helpful?) [6]	1,880	1,553	4,39
29	Scientific findings of the duration of CO2 storage () [18]	2,276	2,538	12,72
30	Managing deployments (How can the deployment of OAE operations be effectively managed to ensure precise application, minimal environmental disturbance, real-time monitoring, compliance with legal and navigation	2,215	2,282	2,91
31	Availability of feedstock, alkaline material	1,810	2,289	6,20
32	OSE field trials were carried out before 2040 (yes or no? A few or many?)	2,285	2,220	6,20
33	Success of other CDR solutions or pathways (is mCDR (cost) competitive or not?)	3,157	2,875	8,64
34	State of CCS development (Does Germany have a sufficient CCS capacity or not?)	2,347	2,202	10,11
35	Monitoring, Reporting, and Verification capabilities (feasible and reliable enough to include OAE in the Emission Trading System or some or no major advancements?)	2,820	2,807	8,12
36	Direct deployment costs (energy, transport, etc.) and cost effectiveness of OAE	2,019	2,477	6,39
37	Carbon price	2,605	2,869	5,21
38	Economic development of Germany and availability of investments and public funding	3,024	2,345	7,31
39	Trade frictions and disruptions (How volatile will the trade system be in the next decade and how does it affect ability of long-term planning of industries/policies)	3,200	2,009	9,27
40	Management of space and shipping traffic (How can marine space and shipping traffic be effectively managed to integrate large-scale OAE operations without disrupting existing maritime activities, and minimizing envi	2,489	2,345	11,31
41	Business model for and private investment in OAE () [27]	2,668	2,281	6,63
42	Is OAE (research and or deployment) legally allowed (London Protocol, UNCLOS and BBNJ, European and German marine regulatory landscape such as Hohe-See-Einbringungsgesetz, Wadden Sea, etc.)?	2,738	3,546	7,97
43	Are mCDR and OAE methodologies and necessary standards sufficiently regulated or legally enabled (UNFCCC, IPCC reporting requirements, Paris Agreement guidelines, EU Carbon Removal & Carbon Farming ce	2,346	2,816	6,27