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A storyline approach: integrating comprehensive, interdisciplinary research results to create narratives – in the context of the net-zero target in Germany

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With the amendment to the German Climate Change Act in 2021, the Federal Government of Germany has set the target to become greenhouse gas neutral by 2045. Reaching this ambitious target requires multisectoral efforts, which in turn calls for interdisciplinary collaboration: the *Net-Zero-2050* project of the *Helmholtz Climate Initiative* serves as an example of successful, interdisciplinary collaboration with the aim of producing valuable recommendations for action to achieve net-zero CO_2 emissions in Germany. To this end, we applied an interdisciplinary approach to combining comprehensive research results from ten German national research centers in the context of carbon neutrality in Germany. In this paper, we present our approach and the method behind the interdisciplinary storylines development, which enabled us to create a common framework between different carbon dioxide removal and avoidance methods and the bigger carbon neutrality context. Thus, the research findings are aggregated into narratives: the two complementary storylines focus on technologies for net-zero CO_2 emissions and on different framing conditions for implementing net-zero CO_2 measures. Moreover, we outline the *Net-Zero-2050* results emerging from the two storylines by presenting the resulting narratives in the context of carbon neutrality in Germany. Aiming at creating insights into how complementary and related expertise can be combined in teams across disciplines, we conclude with the project's lessons learned. This paper sheds light on how to facilitate cooperation between different science disciplines with the purpose of preparing joint research results that can be communicated to a specific audience. Additionally, it provides further evidence that interdisciplinary and diverse research teams are an essential factor for defining solution spaces for complex, interdisciplinary problems.

KEYWORDS

interdisciplinary research, storyline approach, net-zero, carbon dioxide removal, circular carbon approach

1 Introduction

Against the background of the urgency to act on the climate crisis and Europe's promise to achieve net-zero CO_2 emissions[1] by 2050, the project *Net-Zero-2050* was initiated in the framework of the *Helmholtz Climate Initiative*. *Net-Zero-2050* consisted of an intercultural and interdisciplinary team of 80 researchers from ten research centers within the German Helmholtz Association, the largest scientific research organization in Germany. Interdisciplinary and diverse research teams that join forces have been found to be beneficial to achieve holistic outcomes with increased scrutiny (Bates et al., 2024; Kreuter et al., 2020). The goal of the project was the integration of the extensive scientific expertise within the Helmholtz centers to carry out a comprehensive assessment of options and the development of possible recommendations for action that contribute to achieving the net-zero target in Germany. Thus, *Net-Zero-2050* generated knowledge in the context of national carbon neutrality, covering a wide range of associated research topics. The year 2050 was used as this was the target year in the German climate law at the time the project was launched. In research phase 1, which ran from July 2019 until March 2022, the project combined an overarching assessment of CO_2 reduction options, complemented by two case studies to bridge science and practice, with the assessment of options for Carbon Dioxide Removal (CDR) presented in Box 1 (Net-Zero-2050, 2022). In this context, a strong focus lay on new technologies to tackle hard-to-abate emission sectors as well as removing CO_2 from the atmosphere.

To summarize and to narrate the multi-faceted spectrum of this interdisciplinary collaboration, we used the storyline method and customized it to integrate the research results of the project. Aiming at providing a structured overview of the vast research findings, they were combined in two interlinked storylines. The choice of the storylines' focus and content was based on the expertise of the project team on the one hand and the need for scientific knowledge on the implementation possibilities of net-zero CO_2 emissions measures in Germany on the other. The specific occasion and primary purpose for creating the storylines was a main *Helmholtz Climate Initiative* conference where the interim research results were presented to high-level representatives of the German research community as well as to external stakeholders. Thus, the target group for the storylines was firstly only the scientific community. The subsequent step, which falls outside the scope of this paper, was to prepare the storylines in a format that is relevant and useable for different practitioners. One example of this is the final study of the project (Jacob et al., 2023), which used the storylines as a basis. Hence, creating these storylines also served as a test run to rehearse the later communication of the results, e.g., to policy makers.

In the literature, there is a number of examples in different research areas and sectors (e.g., education, health and policy) where the authors found that using narratives and stories can be an effective approach to communicate scientific evidence (e.g., Shanahan et al., 2018; Shaffer et al., 2018; Schlaufer et al., 2022). Jones and Anderson Crow (2017) explored the "science of stories" and argued that narratives are highly influential elements in the social realities of human beings, which is why it is beneficial to address and connect with audiences by means of gripping stories. This way of communicating can increase the importance of the issue for people as well as their connection to the topic. For these reasons and to emphasize the interdisciplinary nature of the project, we opted for developing intertwined and at the same time overarching storylines: a storyline on the framing conditions for implementing measures for net-zero CO_2 emissions "Accelerating Action" and a technology-based storyline "From Source to Sink" (see Figure 1). The scientific content of the wide-ranging *Net-Zero-2050* sub-projects was complemented with a qualitative context by means of the storylines. In this way, we could pave the way to integrate individual and often single-disciplinary sub-project results into a

1 Net-zero CO_2 emissions signifies that anthropogenic sources of CO_2 to the atmosphere are balanced by anthropogenic activities that either enhance natural carbon sinks or remove CO_2 from the atmosphere by means of different technologies.

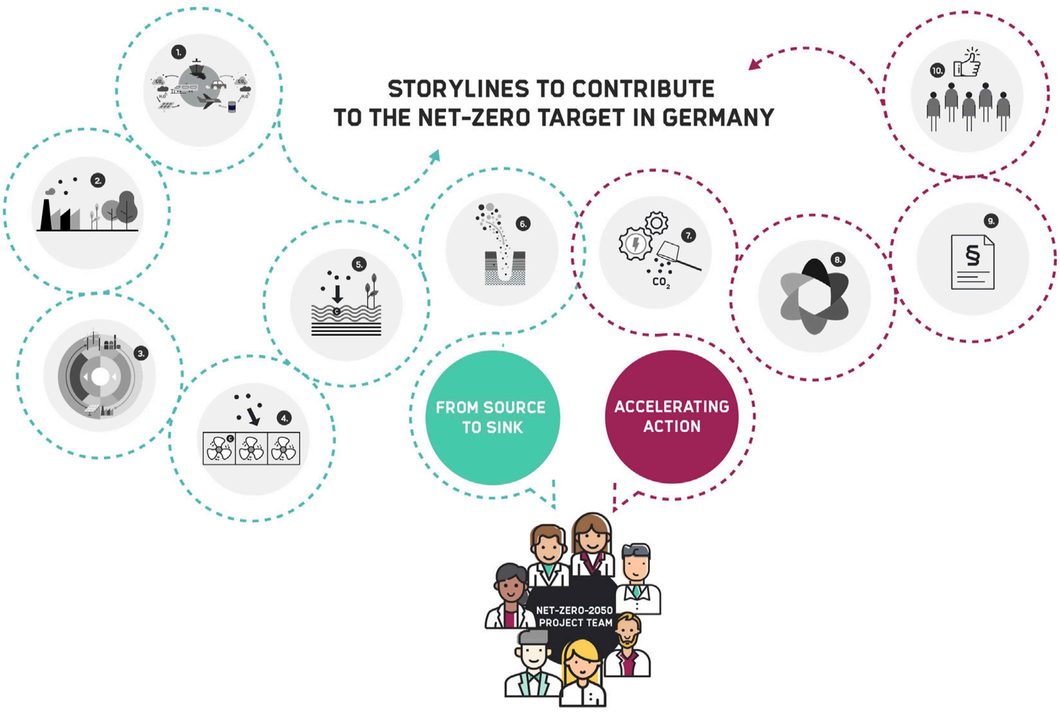

FIGURE 1
The figure visualizes the two intertwined *Net-Zero-2050* storylines that are based on the interdisciplinary, interim research results of *Net-Zero-2050* phase 1. The storyline "From Source to Sink" consists of the six central topics: 1) Conversion of CO_2 into fuels, 2) Bioenergy with carbon capture and storage (BECCS), 3) Carbon loop concept for energy storage, 4) Direct air carbon capture (DAC), 5) Biological CDR options, and 6) CO_2 distribution networks. The "Accelerating Action" storyline includes four central areas: 7) Combined CDR options and energy scenario approach, 8) Feasibility assessment of CDR options, 9) Regulatory framework for deploying CDR options, and 10) Societal acceptability of CDR deployment. (Source and copyright: Helmholtz Climate Initiative/Julia Blenn).

bigger picture and thus create an added value which results in more than the sum of its individual parts.

The present study describes the method to achieve this objective and the content of the storylines in three sections. First, the storylines methodology and key options for net-zero CO_2 emissions reduction, avoidance and removal are explained, linking them to *Net-Zero-2050*'s areas of activity (see Section 2.2). This includes a brief outline of the relevant system with which the project is linked: it considers the multiple facets of reaching net-zero from a systemic perspective as comprehensively as possible (Köhnke et al., 2023). Second, the storylines, with a focus on technological options (biological and chemical) and the framing implementation conditions, are presented as the result of the method. Third, key aspects of the working processes and the lessons learned are described to provide useful insights, success factors and recommendations for similar interdisciplinary approaches and future project phases.

2 Materials and methods

2.1 The interdisciplinary storyline approach

The storyline method is used in different contexts and is hence defined in several ways. In the context of representing uncertainty in physical aspects of climate change, Shepherd et al. (2018) explained a storyline as "a physically self-consistent unfolding of past events, or of plausible future events or pathways". Alcamo (2008) defines storylines as qualitative scenarios, which are generally narrative texts. In addition, Alcamo (2008), p. 124) states that "well-written storylines can be an understandable and interesting way of communicating information about the future, at least as compared to dry tables of numbers or confusing graphs". Hence, the focus of this method lies on a qualitative understanding of the given element and the corresponding context instead of on quantitative precision. In line with this, Shepherd et al. (2018) explain the importance of episodic information, i.e., qualitative information, for humans to grasp information and turn it into action. Difficulties to take and act on information rather occur if solely information that is outside their experience is used, i.e., quantitative, precise information. Thus, episodic information is to be included when scientifically developed storylines are used to communicate information that is tangible. Beyond this, storylines with qualitative components enable to present the findings of several different experts simultaneously (Shepherd et al., 2018). Jones and Anderson Crow (2017) illustrate in particular the necessity of a story's moral, i.e., the main piece of information that the audience learns from the story. The authors specify the existence of good morals as a prerequisite for the content to be implemented later (in this case in a policy context). The better the story is told, the more likely it is that the audience will remember the moral afterwards. In view of these characteristics and benefits, the storyline approach was selected and customized to integrate the *Net-Zero-2050* results.

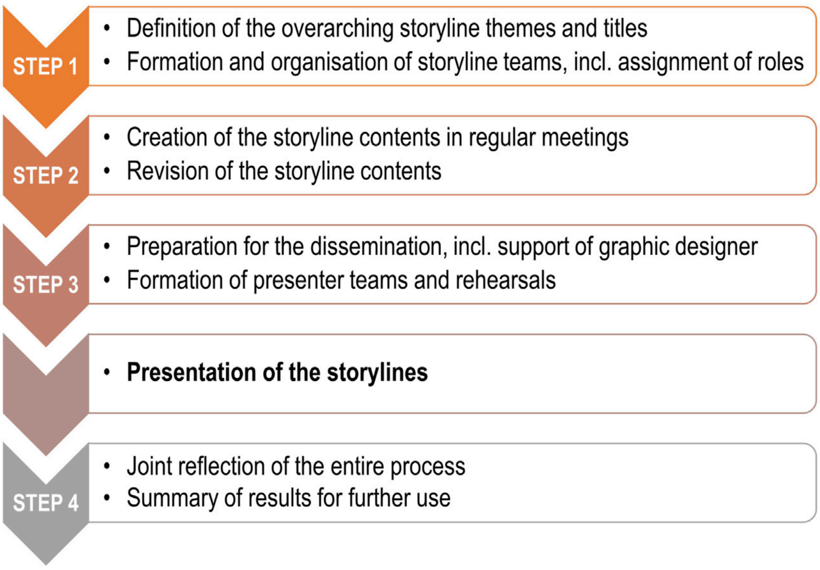

FIGURE 2
The four steps of the interdisciplinary storyline approach.

Hence, an approach was designed that was specific to the research team as well as to their findings and integrated both. The collaborative nature of this method also supported the interdisciplinary approach in the diverse team (i.e., age, gender, culture, disciplinarity). The interdisciplinarity of the *Net-Zero-2050* team was deemed important, because bringing together diverse perspectives, skills and other aspects is a key factor to successfully meet the project's research objective (Bammer, 2008). The process was therefore designed and structured in a way that offers a supportive context and that prevents participants from feeling overwhelmed or overburdened (Bates et al., 2024). We refer to our approach as 'interdisciplinary storyline approach', which we define as follows: individual elements, which are based on interdisciplinary, quantitative, and qualitative research results, have been coherently combined into storylines. The interdisciplinary storyline approach can be divided into four steps, which are described hereafter (see Figure 2).

The first step was to discuss and define the overarching storyline themes with the whole team of 80 researchers. Given the project's research areas (earth and environment, matter, key technologies, energy, information, and data science), it was jointly decided to develop two storylines: a technology-based storyline and a storyline on the framing conditions for implementing net-zero CO_2 emissions measures. Thus, two teams of about ten researchers – predominantly consisting of early-career researchers – were then formed and their collaboration organized. Among other things, this meant communicating the rules of participation and the expectations as well as jointly defining the individual tasks, responsibilities, and deadlines. In both teams, the researchers were able to enrich the respective focal points of the two storylines with content based on their skill sets and research results. Furthermore, three stewards per storyline were identified who coordinated the teams, i.e., they were responsible for schedules, the exchange with the other team, the distribution of responsibilities and for the compilation of submitted storyline contributions. Since the participating researchers were spread across Germany, the storylines were created using online tools.

In the second step, the storylines were created in regular large collaboration meetings. This step involved an idea generation process, content creation and a revision process. During the content creation, the storylines' manuscripts were constructed in an iterative fashion. A draft was created by the storyline teams, which was then adjusted and completed during and between meetings. For the revision process, each storyline was presented to and iterated with the entire consortium twice. The aim of the first revision meeting with the principal investigators was to identify and clarify the strategic cornerstones of the storylines. The purpose of the second revision meeting with the early-career researchers was to ensure that all relevant content was part of the storylines, including the storylines' key messages (morals). Subsequently to these meetings, the storylines were further adapted and refined according to the feedback from the revision.

The third step consisted of the preparation for the dissemination. The storylines were primarily used to present the research results at a conference with representatives of the research community. A graphic designer received the final presentations and ensured that the scientific content could be communicated in a visually appealing and consistent manner, establishing a brand. Additionally, presenter teams, including replacement speakers, were formed for both storylines, consisting of one person from each storyline team. These teams met with each expert of their storyline teams to guarantee that all storyline elements were communicated appropriately. As a final step, the overall presentations were rehearsed several times with a test audience, which ensured that the guiding thread of the storylines ran through the entire presentations. This was followed by the presentation at the major conference.

The fourth step was to reflect on the whole process of creating and presenting the storylines. For this purpose, a joint meeting was organized about a week after the conference. The following questions were discussed at the meeting: 1) Was the purpose of the storylines clear to all of us? 2) Were our roles and responsibilities well defined, understood and followed? 3) Did we have the tools and resources we needed to achieve our objectives? 4) Did we learn from each other? 5) What are our most important lessons learned?

The joint reflection was important because it was already clear at this point that overarching storylines should also be developed for the final conference of the research initiative. This was decided by the project management after the event, as the audience's feedback on the storylines was extremely positive. Hence, the results of the meeting were recorded in writing, made available to the entire team and used again as part of the preparations for the final conference about a year later. The exercise furthermore motivated the research team to compile a scientific publication that was to incorporate all the elements of the two storylines bringing it all together, led by two of the early-career research stewards of the exercise (Mengis et al., 2022)

2.2 Definition of the considered systems

To remove CO_2 from the atmosphere, several options have been proposed that entail either biological, chemical, or combined processes. In addition, the captured CO_2 can also be used, creating a so-called circular carbon approach where the CO_2 is eventually released back into the atmosphere. In the following, the main options that were included in the research of *Net-Zero-2050* are briefly summarized.

1) Direct air carbon capture and storage (DACCS) combines technologies that first capture CO_2 out of the ambient air through chemical processes with carbon dioxide absorbing materials. Subsequently, the CO_2 is purified, concentrated, and sequestered in geological storage sites. Quality of storage in the underground ranges from recoverable CO_2 to chemically fixed carbon over geological times in minerals (Helmholtz-Klima-Initiative, 2020; Smith et al., 2023).
2) Bioenergy with carbon capture and storage (BECCS) combines biological and chemical processes: First the natural process of photosynthesis to remove carbon from the atmosphere is used, afterwards the carbon is captured using chemical processes. If the emitted carbon dioxide is captured and then stored in geological storage sites, CO_2 is removed from the atmosphere (Borchers et al., 2022).
3) CO_2 can also be removed from the atmosphere by means of biological CO_2 removal options. This includes, *inter alia*, increasing the terrestrial or marine biological carbon sink, e.g., rewetting peatlands, restoring seagrasses or changing agricultural practices in a way that the soil carbon content is increased (Helmholtz-Klima-Initiative, 2023a; Smith et al., 2023).
4) In a circular carbon approach, CO_2 is firstly removed from the atmosphere using DAC or BECC options. In contrast to storing the CO_2, it is re-used and afterwards it re-enters the atmosphere. To use the CO_2, it is transformed with renewable energy and hydrogen to be utilized as an energy carrier or chemical feedstock. Point source carbon capture and use (CCU) is a further example for a circular carbon approach where sources of exhaust gases are used as a source of CO_2. Here, the CO_2 concentration is high compared to the concentration in the ambient air. In particular, in the process of direct air carbon capture and use (DACCU), the captured CO_2 is converted together with H2 into materials that can be used in industrial processes as substitutes for fossil carbon materials. Thereby, emissions that would have occurred are either avoided or the CO_2 is converted, with H_2 and energy input, into alternative fuels for "hard-to-abate" sectors (Helmholtz-Klima-Initiative, 2023b; Prats-Salvado et al., 2022).

3 Results and discussion

As described in the section about the method, the focus in the following two *Net-Zero-2050* storylines towards national carbon neutrality was set on providing qualitative information. These are primarily based on numerical research results as well as on qualitative findings. In addition to that, the purpose of creating two complementary storylines was to emphasize the importance of both topics: the different technologies for net-zero CO_2 emissions and the framing conditions. The project findings were thematically divided among both storyline topics to thus clearly demonstrate the importance of both topics. The framework requirements mentioned in Storyline one must be met to be able to implement the technologies mentioned in Storyline 2. The storylines as shown in the following two sections (in italics) correspond to the spoken texts of the presentations of the storylines.

3.1 Storyline 1: "Accelerating Action"

In the first storyline "Accelerating Action", the focus is set on the aim to accelerate climate action in Germany. The title and the content of the storyline were identified by the storyline teams to provide a connecting analytical framework. To link the individual project results, they were placed in a common context and thus, their relative importance and their relationship to each other could be demonstrated. This storyline focuses on specific aspects related to the framing conditions. It does not include a discussion of all related aspects because they were out of the scope of the *Net-Zero-2050* project.

In a first step, the project's system boundaries and systems approach for assessing CO_2 emissions were specified (Köhnke et al., 2023; Thrän et al., 2021). *These included the geographic limit of Germany within the European context, the time frame until 2050 and the CO_2 budget after 2021 for Germany that is in line with a 1.5°C trajectory for global mean temperature change* (Mengis et al., 2021). *The importance of considering contributions from all sectors to achieve a net-zero trajectory as well as the need to give tangible form and limitations to the CO_2 emission budget led to an interdisciplinary assessment of the system capacity on how net-zero can be achieved in Germany. In line with this, Net-Zero-2050 combined the expertise on single CO_2 removal options with* *the expertise on how actions on climate change can be accelerated in the German framework. Four central areas for urgent action were identified:*

The regulatory framework for the deployment of CO_2 removal options in Germany: It is crucial to investigate and assess how the regulatory framework at international, European and national levels can hinder or support the market uptake of CDR measures and take account of the related risks and co-benefits. In Net-Zero-2050, the focus is set on investigating how CO_2 removal options are governed in the existing climate regime (Markus et al., 2021a; b) *and how regulations should be designed to enable the deployment of these options* (Markus et al., 2020). *The results included a comprehensive set of aspects that need to be addressed by legislatures. The results also indicate that the existing regulatory frame at the national and EU level is not adequately prepared to guide the deployment of CO_2 removal options* (Markus et al., 2021b; Schaller et al., 2022). *Further improvement, however, requires both sound conceptualizing and balancing measures of mitigation, CDR and adaptation* (Markus et al., 2021b).

The societal acceptability of CDR deployment: One of the project's priorities is to investigate the needs and concerns of stakeholders by involving key actors. Different engagement approaches were identified. The stakeholder activities can be assigned into three levels, i.e., 1) understand: this level is based on a one-way communication channel. We gather information from stakeholders; 2) exchange: this level is based on a two-way communication channel. At a certain point of time, the status of work within Net-Zero-2050 is discussed with stakeholders and feedback is incorporated; and 3) co-development: this level is based on a regular two-way communication channel. The exchange with stakeholders takes place several times in a row on the same topic (El Zohbi et al., 2021). *It is assumed that a potential market uptake of CDR options can be accelerated if the resistance from stakeholders can be identified in advance. The project's analysis shows that co-development can allow for acceleration of the implementation of related infrastructure by providing the possibility of addressing concerns early in the planning phase. A co-design for a comparable heat storage project that is equally subjected to the German mining law reveals major criteria for storage in the deep subsurface such as transparency, assessment of alternatives, economic viability, and groundwater and seismic monitoring. Addressing these criteria together with the public in an early planning phase has proven to accelerate the permitting process.*

Following the hypothesis that a feasibility assessment of CO_2 removal options needed to compensate for residual emissions for a net-zero target can accelerate the climate action, feasibility was assessed along six dimensions: system utility, technological, economic, institutional, environmental and societal dimension. In this context, Net-Zero-2050 has developed the Technology Assessment Framework (TAF), a new tool that is contextualized, scaled-down and comprehensive in terms of aspects covered and tailored to the national context (Förster et al., 2022). *The primary objective is to inform and catalyze a discussion with and for national policy. Furthermore, 16 CO_2 removal concepts were designed that provide promising options for carbon removal in the German context (thirteen of which have been described in* Borchers et al. 2022*). These concepts of CO_2 removal options were evaluated concerning their feasibility across the different categories of the Technology Assessment Framework* (Förster et al., 2022) *and tailored to the G. context* (Borchers et al., 2024). *This assessment accordingly brings together the expertise from the entire project to provide a comprehensive evaluation and comparison of possible CO_2 removal measures that are in addition to CO_2 emission reduction options necessary to achieve net-zero CO_2 emission in Germany.*

In addition, Net-Zero-2050 worked on a combined CO_2 removal options and energy scenario approach. It complemented the CO_2 removal options with a comprehensive outlook on the necessary emission reductions from the main CO_2 emitting sector, the energy sector, which encompasses generation, distribution, storage, infrastructure, and supply of electricity as well as heat. Here, starting from the normative target scenario "Net-Zero Germany" by 2050 under a limited total CO_2 budget, the backcasting approach identifies actions in all energy sectors (buildings, industry, transport, and energy conversion) needed to contribute on the way to reach this scenario (Harpprecht et al., 2022; Simon et al., 2022). *This quantifies on the one hand the necessary effort and investment to mitigate CO_2 emissions and the additional requirements on energy infrastructures (*Simon et al., 2022*). On the other hand, it identifies the order of magnitude of hard to abate or residual CO_2 emissions* (Harpprecht et al., 2022), *which still need to be compensated for by CO_2 removal options. Summarizing, one main finding was that the implementation of CO_2 removal options in Germany will only be successful if the energy system is drastically transformed, including the deployment of carbon neutral technologies.*

3.2 Storyline 2: "From Source to Sink"

The second *Net-Zero-2050* storyline "From Source to Sink", comprised the results obtained in the area of CO_2 mitigation approaches. This included chemical, biological and hybrid options for CO_2 capture, storage and usage as well as CO_2 mitigation approaches related to energy production, e.g., fuels synthesis with CO_2, H_2 and renewable energy (Sun-to-Liquid, 2021). The context for storyline 2 was that 1) the use of fossil carbon has to be limited to a total CO_2 budget and 2) circular carbon approaches need to be established (see Section 2.2). The broad concept of the storyline was to provide a narrative explanation from completely chemical to exclusively biological CO_2 removal options. The aim was to show where major differences and similarities exist, resulting in synergies and trade-offs in the conclusion of the storyline. In the following, the details on these priority topics that form this storyline and its conclusions are summarized (for details compare also Mengis et al., 2022).

Direct Air Capture (DAC) was investigated by Net-Zero-2050. In particular, the technology readiness level (TRL) of DAC, the energy demand and the cost of DAC technologies were assessed. In this context, it was found that there is scope for improvement in terms of energy demand especially for DAC. Hereby, the most potential for improvement lies in the scale up of the production and innovations in the sorbent material. Furthermore, Net-Zero-2050 started research on the recently developed technology electro-swing-adsorption (ESA), which is more energy-efficient compared to established Low and High-Temperature-DAC plants. Those ESA-modules offer a great variability in sizing and could potentially be employed in a wide variety of applications. Integrating DAC-technologies directly into a *heating, ventilation, and air conditioning (HVAC) system, for example, could generate synergies between the building services engineering and DAC. Additionally, unutilized areas are capitalized and small players could participate in a future carbon dioxide market, creating new business opportunities, especially if the CO_2 is then converted into valuable products like hydrocarbons. Net-Zero-2050 assumes this method – for which it has coined the term "crowd-oil" – to be a pioneering technology. Due to a relatively low concentration of CO_2 in the ambient air the DAC processes are very energy consuming. In contrast to that, CO_2 capture at concentrated point sources is less energy consuming, as the concentrations of CO_2 in the exhaust gases are higher. The point sources can be fossil-based, like coal power plants, or renewable, e.g., biogas plants (see BECCS-related section below). Newer developments such as membrane separators could increase the efficiency further.*

Within the framework of Net-Zero-2050, eight technologies for Bioenergy with Carbon Capture and Storage (BECCS) have been analyzed: three pathways for biogas production with combined heat and power (CHP) generation (each based on different type of feedstock), biogas upgrading to biomethane, biomass combustion for CHP, gasification for synthetic fuels, and fast/slow pyrolysis for bio-oil/biochar production. All these options are characterized by relatively high TRL (TRL 7–9), promising their possible near-term deployment. An important attribute of BECCS is its ability to generate energy (e.g., heat, electricity, fuels), which is particularly useful in the advancing decarbonization and energy transition as it supplies the demand for flexible renewable energy sources. However, BECCS as a land-based concept, faces concerns related to its possible negative impacts on land use and biodiversity, especially when deployed on large-scales. To address these issues in Net-Zero-2050, particular attention has been given to sustainably sourced biomass, including novel approaches like paludiculture and macroalgae farming (Borchers et al., 2024).

Net-Zero-2050 includes research activities on a novel carbon loop concept for energy storage, which is based on the Power-to-X-to-Power approach. Applying this concept, two scenarios for a CO_2 neutral German power sector in 2050 were analyzed. The difference between both is that, in one case, the net electrical energy consumption is covered by a residual share of natural gas. The CO_2 that is emitted must be stored permanently in deep subsurface storage. In the other scenario, the net electrical energy consumption is provided by renewable energies. The latter system does not need storage of CO_2 that is permanent because the amount of CO_2 stored matches the amount of CO_2 extracted. However, the demand for temporary storage is higher in this scenario. All this includes the supply of hydrogen, since a large electrolyzer is integrated to supply H2 for the PtX methane production. Therefore, this system also includes hydrogen production, storage, and distribution. Also, it is possible to use this electrolyzer to supply other hydrogen consumers, which directly avoids CO_2 emissions (Fogel et al., 2022).

For the conversion of CO_2 into fuels, two basic steps were identified. First, CO_2 and H_2O must be converted into CO and H_2 respectively. Second, the mixture of these two chemicals (which is often referred to as synthesis gas) is processed into the final fuel. In the frame of the Net-Zero-2050, three pathways were analyzed for the production of synthesis gas: the solar thermochemical cycle, the PEM electrolysis with rWGS and the co-electrolysis with a SOEC. Similarly, methane, methanol and hydrocarbon mixtures produced with the Fischer-Tropsch process were considered as the three possible final fuels. The results showed that the solar thermochemical cycle was the most energetically efficient process since it can directly convert heat into fuel with a minimal electricity input (Prats-Salvado et al., 2022). *This is important because significant energy losses occur in the conversion of primary energy into electricity, which is the main energy input of the electrolysis pathways* (Dittmeyer et al., 2021).

Another focus of the Net-Zero-2050 was the integration of the fuel production with the available renewable energy infrastructure. For this reason, a decentralized unit integrated with a building was designed and modelled. For this case study, a solar thermochemical cycle was considered to produce synthesis gas and the chosen final product was Fischer-Tropsch oil containing hydrocarbons between C5 and C50. To meet the heat demand of the process, a parabolic dish that could be installed on the rooftop of a building was sized and the required area of PV panels integrated with the buildings' façade was determined for the calculated electricity needs. The results confirmed the viability of these decentralized systems and the remarkable synergies with the DAC when integrated with the buildings' HVAC system (Prats-Salvado et al., 2021).

In the research field of CO_2 distribution networks, Net-Zero-2050 analyzed a CO_2 pipeline network connecting industrial point sources in Germany to permanent and temporary CO_2 storage sites in porous aquifers. The focus is set on a CO_2 distribution network, which is cost-efficient and based on the idea of regionally clustering large industrial CO_2 sources. In particular, this implied that CO_2 pipeline costs can be reduced if regional clustering is optimized.

Three biological CO_2 removal options that contribute to achieving carbon neutrality were assessed in the Net-Zero-2050: Land use management, peatland rewetting and seagrass blue carbon. Biological CO_2 removal differs mainly from chemical and hybrid options because it does not require additional energy input. Regarding the management of agricultural soils, a modelling approach on the emission reduction potential in agricultural topsoil was used to spatially estimate how much emissions from top soils can be reduced. The most promising soil management scenario includes temporal intercropping, changing crop rotation, conversion to grassland and increasing organic fertilizer applications. Such details are made accessible to farmers and stakeholders via the Soil Carbon App developed by Net-Zero-2050 (Net-Zero-2050, 2022). *Peatlands store millennia of accumulated organic carbon, but when drained for agricultural use, these systems emit large amounts of CO_2. To avoid these emissions, drained peatlands need to be rewetted. Net-Zero-2050 quantified the annual CO_2 emissions of peatlands in northeastern Germany after rewetting* (Kalhori et al., 2024). *These vary by sites and depending on site history and water table management, the transition from CO_2 source to sink will happen sooner or later. In one of the experimental sites, CO_2 emissions initially continued after rewetting and decreased a decade after rewetting, resulting in a source-to-sink transition 16 years after rewetting* (Kalhori et al., 2024). *The other rewetted site turned to a larger CO_2 sink immediately after rewetting. Seagrasses are marine plants that have an exceptional ability to capture CO_2 that has dissolved into the oceans from the atmosphere and sequester it long term as organic carbon below ground. Net-Zero-2050 quantified the carbon stock and sequestration rates of seagrass meadows along the German Baltic Sea coast via field measurements. The organic carbon* *stock stored beneath seagrasses in the Baltic S. coast of Germany is substantial and re-emission of this stock can be prevented via the conservation of existing seagrass meadows* (Stevenson et al., 2023). *Carbon dioxide removal by these habitats can be enhanced by expanding the seagrass area via restoration activities, thereby gaining negative emissions* (SeaStore, 2023).

3.3 *Net-Zero-2050* storylines summary and discussion

Summarizing storyline 1, the *Net-Zero-2050* cluster concluded that, to accelerate action in Germany, it is necessary to 1) provide an assessment of the regulatory framework for CO_2 removal options, 2) support the implementation of CO_2 removal options by considering the concerns and needs of key actors, 3) provide an impartial assessment of CO_2 reduction and removal measures that need to be taken into account to achieve net-zero by 2050.

The second storyline shows that a large number of different CO_2 avoidance, reduction and removal options are available in Germany and that each can contribute to achieving the net-zero target. This means that these approaches need to coexist in their respective applications and that a sensible combination of them is necessary. However, such a portfolio must take into account the synergies and trade-offs between the different approaches to CO_2 removal, which was addressed in Borchers et al. (2024).

The two storylines concluded with the following key statements: Developing the scientific knowledge of technologies for circular carbon approaches and decreasing the energy demand of CO_2 capture by new approaches were prioritized within *Net-Zero-2050*. By comparing and identifying CO_2 reduction and removal potentials and benefits, *Net-Zero-2050* aimed to provide knowledge to support increasing the acceptance and the successful implementation of the identified options in society. The project's analysis showed that Germany will not be able to achieve net-zero CO_2 emissions by 2050 within national borders without compensation of residual emissions (Simon et al., 2021; Simon et al., 2022; Mengis et al., 2022). For a maximum reduction, a significant expansion of renewable power capacity, including power grid and hydrogen infrastructure is necessary (Xiao et al., 2021a; Xiao et al., 2021b). It is thus also necessary to import sustainable chemical energy carriers (e.g., green hydrogen, synthetic methane or synthetic fuels). In addition, the *Net-Zero-2050* recommendations included reaching out to national and international science partners, involving stakeholders and industry partners, improving the overall impact and visibility of Helmholtz research in the climate field and helping overcome the usual institutional barriers within the science community. The storylines ended with the final message: An integrated solution is necessary, taking CO_2 out of the atmosphere, back into use and storage – sustainably.

4 Conclusion

In this paper, we have presented our approach to combine and outline the interdisciplinary *Net-Zero-2050* results from ten national research centers in two complementing storylines as contributions to achieving the net-zero target in Germany. Rather than merely communicating the pure facts, we wanted to generate knowledge by combining the results, putting them into a bigger picture and – by using a narrative explanation approach – addressing a specific target group. The interdisciplinary storyline approach enabled us to create the connection between emissions reduction, avoidance, and the implementation of different CDR methods, to create a greater context and two storylines that encompass all research results.

With our approach, we have provided further evidence that interdisciplinary and diverse research teams are an essential factor for solution-oriented collaborative research. An internal, joint discussion and reflection on the working processes revealed that the project partners considered the collaborative effort on the storylines highly successful and helpful to meet challenges unique to interdisciplinary research projects. As a result, several lessons were drawn for future collaborations. Concerning the storyline teams, the continuous support by all project partners was identified as an essential success factor. Another important factor was to assure the sufficient visibility of each contributor. In addition, the support of the graphic designer was considered advantageous for preparing outreach and improving communication, but it should have been provided right from the start. Moreover, specific communication needs of the project team must be considered, e.g., researchers from different research fields had different understandings of the same terms because the same words can be used differently in different contexts (e.g., CO_2 with a positive or negative connotation). Regarding time and human resources, the role of the stewards was very time consuming, which is why time availability should be a consideration in the role allocation process. Given that the development of storylines was not part of the *Net-Zero-2050* project proposal, we found that future proposals should ensure that adequate resources are allocated to such formats. Overall, our approach showed that 6 weeks preparation time is sufficient after having identified the purpose and target groups. Finally, the process reflection as well as reflecting on personal roles was found to be helpful.

In view of the added value of developing the interdisciplinary storylines, the knowledge transfer between experts from different entities, who rather rarely exchange and share knowledge in such detail, was considered one of the key accomplishments from this process and from working in an interdisciplinary context. Thus, the storyline development was a comprehensive learning experience in terms of capacity building and conducting interdisciplinary research and future outreach. Another special feature of the process was that many linkages between the single work packages were created. As a result, a joint identification for all researchers with the overarching project goals was created, which in turn enabled a productive collaboration. In particular, the project partners were more willing to join forces and contribute to joint products (Jacob et al., 2023; Mengis et al., 2022; Förster et al., 2022; Borchers et al., 2022 & 2024), including this paper. As a significant improvement for large projects relevant for the future project period and beyond, the storylines were also enablers of mutual continuous support by all partners. While these are useful findings, the interdisciplinary storyline approach was used once under the specific conditions. This does not ensure that it would be as effective in other research settings. To this end, the following possible challenges that research teams may face need to be considered: The development of storylines can take a considerable amount of time, it requires commitment by the entire research team and the storyline content cannot include detailed results. Future studies on the application of the interdisciplinary storyline approach would help to further clarify the approach.

In summary, the interdisciplinary storyline approach was found to be an appropriate and innovative way to combine and present overarching topics and findings of the interdisciplinary and diverse research activities in narrative form. It supports integrating detailed in-depth studies with overarching systemic results. Moreover, this concept can also be useful in the context of diverse outreach activities and communicating scientific results to different and broader target groups. To tackle major societal challenges like climate change and the transformation of society and industry on the way to a net-zero Germany, large and interdisciplinary projects and research programs are urgently needed and we hope that our findings will be valuable in enabling and facilitating such cooperations.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

FK: Writing–original draft, Writing–review and editing. BS: Writing–original draft, Writing–review and editing. LB: Writing–original draft, Writing–review and editing. MB: Writing–original draft, Writing–review and editing. TB: Writing–original draft, Writing–review and editing. RD: Writing–original draft, Writing–review and editing. MD: Writing–original draft, Writing–review and editing. JE: Writing–original draft, Writing–review and editing. JF: Writing–original draft, Writing–review and editing. EG: Writing–original draft, Writing–review and editing. KG: Writing–original draft, Writing–review and editing. MH: Writing–original draft, Writing–review and editing. DH: Writing–original draft, Writing–review and editing. AK: Writing–original draft, Writing–review and editing. KK: Writing–original draft, Writing–review and editing. ZL: Writing–original draft, Writing–review and editing. NdM: Writing–original draft, Writing–review and editing. NtM: Writing–original draft, Writing–review and editing. AO: Writing–original draft, Writing–review and editing. EP-S: Writing–original draft, Writing–review and editing. TR: Writing–original draft, Writing–review and editing. IR: Writing–original draft, Writing–review and editing. TS: Writing–original draft, Writing–review and editing. RS: Writing–original draft, Writing–review and editing. ES: Writing–original draft, Writing–review and editing. SS: Writing–original draft, Writing–review and editing. AS: Writing–original draft, Writing–review and editing. TT: Writing–original draft, Writing–review and editing. DT: Writing–original draft, Writing–review and editing. MX: Writing–original draft, Writing–review and editing. DJ: Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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