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On the path to net-zero: Establishing a multi-level system to support the complex endeavor of reaching national carbon neutrality

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Limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C, as agreed in the 2015 Paris Agreement, requires global carbon neutrality by mid-century at the latest. The corresponding carbon budget is decreasing steadily and significantly. To phase out carbon emissions in line with the specified temperature target, countries are formulating their mitigation efforts in their long-term low greenhouse gas emission development strategies (LT-LEDS). However, there are no standardized specifications for preparing these strategies, which is why the reports published to date differ widely in terms of structure and scope. To consider the multiple facets of reaching net-zero from a systemic perspective as comprehensively as possible, the authors propose the Net-Zero-2050 System: A novel, transferrable systems approach that supports the development of national endeavors toward carbon neutrality. The Net-Zero-2050 System is defined by three interconnected components: The Carbon-Emission-Based System, the surrounding Framing System and a set of system boundaries. For both systems levels, IPCC approaches were used as a basis and were then adjusted and supplemented by Net-Zero-2050. We suggest applying the Net-Zero-2050 System—beyond the project environment—in carbon emission based contexts at different levels. Especially at the national level, this would improve the comparability of the different national strategies to achieve carbon neutrality.

KEYWORDS

net-zero, carbon neutrality, mitigation, carbon dioxide removal, decarbonization

1. Introduction

The Paris Agreement invites signatory countries to formulate and submit their long-term low greenhouse gas emission development strategies (LT-LEDS). The LT-LEDS frame the nationally taken efforts toward the Paris Agreement's long-term goal to limit the increase in global mean temperature to well below 2°C, with aspirations toward 1.5°C, compared to pre-industrial levels (UNFCCC, 2022a). Thus, they provide countries with an acknowledged "global policy architecture" (IPCC, 2021, p. 14) to shape their vision and establish a stringent direction for future climate development (UNFCCC, 2022a).

As of March 2022, 51 LT-LEDS (see table "LT-LEDS" in the Supporting Information) have been submitted to the United Nations Framework Convention on Climate Change (UNFCCC). This means that of the 196 Parties that adopted the Paris Agreement in December 2015, only a little more than a quarter have submitted their long-term strategies in response to the UNFCCC's invitation and, therefore, a large number of additional LT-LEDS should still be submitted (UNFCCC, 2022a,b). The latest Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) clearly shows that this—non-mandatory—effort would be worthwhile and absolutely relevant: during the decade 2010–2019, global net anthropogenic greenhouse gas (GHG) emissions were higher than at any previous time in human history (IPCC, 2022a). To halt global warming at a minimum in the long-term, no additional CO_2 emissions should be introduced into the atmosphere from human activities—in other words, CO_2 emissions "must reach "net" zero" (IPCC, 2022a). This is a prerequisite for stabilizing global warming, since CO_2 emissions have a long lasting warming impact on global climate (IPCC, 2022a). Thus, deep emission cuts across all sectors and regions are required to reach net-zero CO_2 emissions globally, unavoidably supplemented by carbon dioxide removal (CDR) from the atmosphere to counterbalance residual emissions that are "hard-to-abate" (IPCC, 2022a).

There is a wide range of CDR methods and corresponding implementation options, ranging from natural sink enhancement to technological and chemical approaches (Borchers et al., 2022; IPCC, 2022a). All of them have in common that they describe human activities removing CO_2 from the atmosphere and storing it temporarily or permanently in terrestrial, geological or marine reservoirs as well as in long-lived products (IPCC, 2022a). A look into the submitted documents reveals that the countries' approaches to the CDR spectrum and corresponding feasibility considerations are widely varying. On the one hand, there is consensus on the relevance of CDR. On the other hand, detailed specifications of how and to what extent CDR should be used are predominantly not provided (Buylova et al., 2021). In line with this, it is relatively challenging to compare the individual LT-LEDS with one another and to really assess the expected contribution to the global goals. Germany, for example, highlights in its Climate Action Plan 2050 the importance of forests and wetlands, soil carbon sequestration. Additionally, carbon capture and utilization (CCU) and long-term carbon capture and storage (CCS) are mentioned as possibilities for the future but are not further developed (BMUB, 2016, pp. 9, 57; Thoni et al., 2020, p. 3). While the plan provides partial insight into the IPCC's six feasibility considerations (see de Coninck et al., 2018) of the proposed CDR options, it does not provide much insight into the nature of the efforts required to reduce or eliminate barriers to improve the feasibility of each option. Germany's climate targets and policies are, however, despite interim updates, considered insufficient to be consistent with the Paris Agreement's 1.5°C temperature goal (CAT, 2021).

The Net-Zero-2050 project, Cluster I of the Helmholtz Climate Initiative, has therefore set itself the task of underpinning Germany's path toward carbon neutrality with scientific evidence. The project results included the calculation of national CDR potentials (Borchers et al., 2022; Mengis et al., 2022) and associated implementation recommendations as well as the design of an energy system transformation path in agreement with a predefined 1.5°C-budget for Germany (Simon et al., 2022). As an overarching action step, the Net-Zero-2050 System was developed to comprehend the anthropogenic systems that need to be transformed in order to achieve national carbon neutrality. A transformation as stated in IPCC's Special Report on 1.5°C global warming (SR1.5) would require scaling up and accelerating the implementation of far-reaching, cross-sectoral and multi-level climate action and removing barriers (IPCC, 2018a, p. 315). To consider the multiple facets from a systemic perspective as comprehensively as possible, the authors propose the Net-Zero-2050 System: a novel, transferrable systems approach that supports the development of national endeavors toward carbon neutrality. It consists of three interconnected components (see Figure 1):

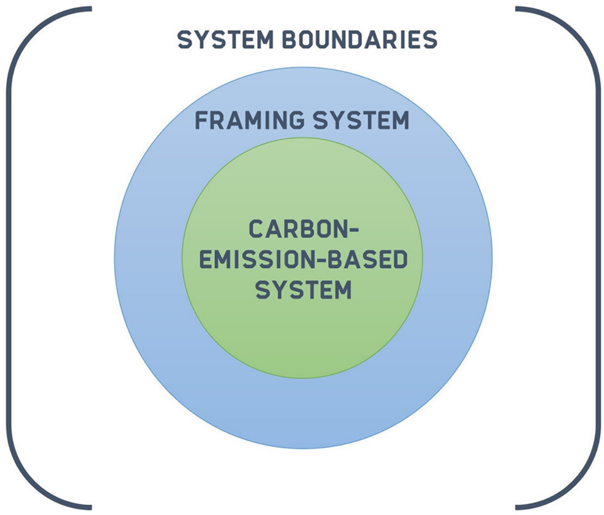

FIGURE 1
Schematic overview of the Net-Zero-2050 System.

- Boundary conditions: Net-Zero-2050 System Boundaries to define general framework conditions and draw clear boundaries.
- Inner level: Carbon-Emission-Based System to comprehensively and transparently capture anthropogenic CO_2 emissions, CO_2 removal and circular CO_2 usage.
- Outer level: Framing System to consider relevant feasibility dimensions to enable rapid implementation.

The aim of this study is to present an approach to design net-zero strategies at different levels. To this end, we have explored methodological options using Germany as a form of testing ground. This study is about the initial step—before a net-zero strategy can be designed. This raises the following core questions: What is an approach to creating a net-zero strategy (at different levels)? What conditions must be in place before a strategy can be developed? What elements must be included in the strategy and what are the key focal points? We address these questions by presenting our approach, the Net-Zero-2050 System.

There are several studies on how to create net-zero strategies for specific sectors or industries. However, to our knowledge, this is the first study that integrates these system components into one comprehensive system, with a strong focus on CO_2 removal and circular CO_2 usage. While it was created for the German context, its strong reference to internationally recognized documents (particularly the IPCC) allows other nations to use it as a template for their own net-zero efforts. We are not aware of a study that can be used as guidance for creating a national net-zero strategy that combines the mentioned elements with a focus on CDR and CCU. In view of this lack of commonly available instructions, a commonly used guidance could enhance the comparability of net-zero strategy reports. On this account, we propose the Net-Zero-2050 System.

To present the Net-Zero-2050 system approach extensively, this paper is structured into four further chapters: Section 2 presents the methods applied for developing the Net-Zero-2050 system perspective; Section 3 describes the system components in detail and discusses the system perspective and its transferability; Section 4 provides concluding remarks.

2. Materials and methods

Two main methods were used to develop the Net-Zero-2050 System: (1) A preparatory literature research to lay the foundations for the system and incorporate the most recent developments from research and relevant gray literature; (2) Dialogues and consultations with internal project partners and with external experts. With regard to the internal project partners, it is referred to an interdisciplinary team of nearly 80 scientists with expertise on the global and national remaining carbon budgets, integrated analyses on scenarios of the German energy system, on circular carbon approaches, carbon dioxide removal and related technologies such as Direct Air Carbon Capture and Storage/Use (DACCS/DACCU) and Bioenergy with Carbon Capture and Storage/Use (BECCS/BECCU) as well as on legal and economic framework conditions. Moreover, the project combined expert knowledge on the potential and integration of subsurface storage solutions with foci on storage and provision of heat/chill in urban areas and the storage and re-use of CO_2 and H_2. Lastly, the Net-Zero-2050 project partners worked on nature-based storage systems, in particular on carbon storage in seagrasses and in organic and agricultural soils. For the dialogues, various formats with different group sizes were chosen to have goal-oriented and constructive discussions. In summary, our research design using different methods and approaches facilitated the integration of the expertise involved in the project into the system development process in the most effective way.

The approaches to set up the Net-Zero-2050 System consisting of system boundaries and two system levels, which interact closely with each other, are outlined in the following sections. Net-Zero-2050 first established the system boundaries, which represent the underlying boundary conditions with regard to the Net-Zero-2050 System. The "inner level" of the Net-Zero-2050 System comprises the Carbon-Emission-Based System and the "outer level" constitutes the Framing System. The chosen approaches to define these system components are briefly outlined below.

2.1. Boundary conditions: Net-Zero-2050 System Boundaries in the German context

The System Boundaries describe the basic scope for action that the interdisciplinary Net-Zero-2050 team was intended to exploit during the project work. Since the System Boundaries decisively determined further project work, they were defined right at the beginning of the project. This enabled the team to work purposefully toward the net-zero target for Germany by the middle of the century and to use the available resources efficiently.

To establish the System Boundaries, i. e. to identify and justify which aspects of national carbon neutrality were to be included, two methods were combined: first, various gray literature sources were studied to find out which System Boundaries were drawn in similar projects. These materials included the studies "RESCUE—Wege in eine ressourcenschonende Treibhausgasneutralität" (UBA—Umweltbundesamt, 2019) and "Unser Fahrplan für ein klimaneutrales Deutschland" (GermanZero, 2020), which were the prevailing net-zero studies in Germany at that time. The desk research was complemented with the IPCC glossary, namely the one of the SR1.5 (IPCC, 2018b), to incorporate definitions of specific terms that are internationally recognized. Based on the results, a draft for the System Boundaries was developed. This proposal was subsequently discussed in detail with the entire project team at a workshop, adjusted and ultimately finalized. This second step was important in order to map relevant aspects from the point of view of the project participants, given their respective expertise.

2.2. Inner level: The Carbon-Emission-Based System

The Carbon-Emission-Based System was created to be able to identify where CO_2 emissions and removals may occur within defined System Boundaries. To approach the complex task of assembling the system, five steps were performed, which are set out in the following.

As a first step, research on gray literature was conducted to examine recent publications at the international level. In particular, a number of national roadmap reports were studied to obtain an overview of the system approaches that are taken internationally. To this end, a number of LT-LEDS reports were examined. As mentioned above, Parties to the Paris Agreement are invited to formulate and communicate LT-LEDS in accordance with Article 4, paragraph 19 of the Paris Agreement. LT-LEDS are officially submitted *via* the UNFCCC and should comprise equitable transition strategies to net-zero emissions, while considering different national framework conditions. Parties are encouraged to update their strategies periodically, as appropriate, in line with the most recent scientific research (UNFCCC, 2022a). The LT-LEDS, examined in a first step for this system definition by Net-Zero-2050, included all reports that were submitted to the UNFCCC by 28 February 2020. The aim was to derive key points that were relevant for assembling the system. It was also important to identify that most of the LT-LEDS reports solely take biological CO_2 removal options into account, while chemical and hybrid options are considered but not elaborated or incorporated into the national long-term strategy. Furthermore, the included sectors were specifically examined which resulted in the finding that the sectors presented in the national reports are not congruent.

Subsequently, it was examined how science approaches the topic, searching for a unified approach to the issue, i. a., considering different sectors. The first step was thus supplemented by studying peer-reviewed research, using mainly sources from the IPCC. These included the comprehensive Assessment Reports on climate change, the Special Report on global warming of 1.5°C and specifically the Methodology Reports (IPCC, 2006, 2019a), which are also the base for the UNFCCC submitted National Inventory Reports (UNFCCC, 2022c). In line with this, the inner level of the Net-Zero-2050 System, the Carbon-Emission-Based System, is hence based on the categories of the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) and its refinement (IPCC, 2019a). In particular, the 2006 methodology report and the 2019 refinement functioned as the starting point for assembling the inner level of the Net-Zero-2050 System, which was thus grounded on a solid scientific foundation for supporting the preparation of national GHG inventories (IPCC, 2019b). The primary reason for modifying the categories of the IPCC guidelines was to place an emphasis on the importance of CDR and CCU for achieving the net-zero goal. Therefore, respective categories were added as main categories (see chapter 3.2).

The third step involved project-internal stakeholders. By means of several discussion rounds, the IPCC-based structure of the Carbon-Emissions-Based System was supplemented and rearranged in collaboration with project partners, who are experts on multiple research topics, to detect potential gaps and, thus, incorporate additional main categories and subcategories. The focus of the internal view represents the expertise that was available in the project itself. It was ensured that all points are listed comprehensively. To prevent a one-sided view, in the next step, the system was presented to external experts having a broad overview of the topic. Moreover, it was agreed with the project partners that the system should be a "living document." This enabled further developments in research to be adequately taken into account at a later date.

To facilitate assessing and evaluating the system's categories, external high-level experts, i.e., experts authoring significant publications in the field and holding leadership positions in leading research institutions were consulted. This step was used to assure that all crucial categories and elements were included and considered. The three consulted experts are internationally acknowledged in the field of carbon neutrality research and, thus, have extensive knowledge about current developments of how countries are aiming to achieve net-zero CO_2 emissions. These four steps were performed in the first year of the project phase.

As described in step three, the Carbon-Emission-Based System was considered a living document. In this last step, the system was thus discussed with the project partners throughout the project at regular intervals to ensure that it was kept up-to-date. In this way, the system composition could be adjusted to adapt it to current developments in the area of CO_2 removal and after a first use case. In particular, a taxonomy for CO_2 removal options was created. This classification required a reallocation of the system categories according to this definition. Hence, two different versions of one of the main categories were established (category 6, see chapter 3.2).

2.3. Outer level: The Framing System

In Germany, a transformation of all economic and social systems is required in complex and interconnected ways to achieve the net-zero target by mid-century. Feasibility of mitigation options is key, thus, a framing system was developed to emphasize what dimensions have to be regarded for accelerated transformation.

To set up the framing system, three methods were combined. First, gray literature was examined to attain an overview of studies on how to achieve carbon neutrality in Germany. The most recent and relevant studies on German net-zero scenarios, which are currently subject of debate in the literature and in the media, include the following five studies: The Ariadne-Report "Deutschland auf dem Weg zur Klimaneutralität 2045" (Kopernikus-Projekt Ariadne, 2021), the Dena—Leitstudie "Aufbruch Klimaneutralität" (Dena, 2021), the modeling commissioned by the German Federal Ministry for Economic Affairs and Energy on the future development of the energy system (Sensfuß et al., 2021), the study "Klimaneutrales Deutschland 2045" (Prognos Öko-Institut, Wuppertal-Institut, 2021) and the study "Klimapfade 2.0—Ein Wirtschaftsprogramm für Klima und Zukunft" (BDI and BCG, 2021). In addition, peer-reviewed literature was consulted to learn more about scientific approaches to the feasibility of CDR options. In particular, SR1.5 was a valuable source of knowledge for this purpose, as it presents six different feasibility dimensions (see de Coninck et al., 2018). Subsequently, these six dimensions' fit to the German context was assessed in light of the studies presented earlier and slightly adjusted. In a final step, external experts from the field were consulted to evaluate the developed framework and improve the reliability and completeness of the defined dimensions.

3. Results and discussion

After presenting the methods and the process of how the Net-Zero-2050 System was created, this chapter presents the corresponding results and discussion. In particular, the three system components of the Net-Zero-2050 System, namely the System Boundaries, the Carbon-Emission-Based System, the Framing System and the respective system elements, are outlined and discussed in the following.

3.1. System boundaries: Net-Zero-2050 System Boundaries in the German context

The system boundaries describe the basic scope for action that the interdisciplinary Net-Zero-2050 team exploited in its project work. First, the consortium agreed on a science-based definition of net-zero that reflects the current state of knowledge. It was jointly decided to take this from the glossary of SR1.5 and adapt it to the German context: Net-zero CO_2 emissions, also referred to as carbon neutrality, signify that by deploying CDR, the residual anthropogenic CO_2 emissions in Germany are counterbalanced by mid-century at the latest (see IPCC, 2018b).

Regarding the temporal boundary, 5–10 years intervals until 2050 were set to be included in the project's results and findings. Geographically, the project focused on Germany as a starting point to achieve carbon neutrality within national boundaries. However, the energy system's interconnection to neighboring countries is also considered. A constraint of the Net-Zero-2050 project was to have the year 2050 set as the target year for reaching carbon neutrality. During the course of the project, an amendment to the Climate Change Act was passed by the German Federal Government that enshrines in law the goal of achieving GHG neutrality already by 2045. However, this discrepancy in the boundary condition was of minor relevance as our results show that the next few years up to 2030 are crucial (Mengis et al., 2022). By 2030, all preconditions must be created and strategies must be implemented to maximally reduce and avoid CO_2 emissions. This is a mandatory prerequisite for achieving the goal of a CO_2- or climate-neutral Germany by 2050 or earlier.

Reducing the complexity of the Net-Zero-2050 System, the focus was set on CO_2, being the largest contributor to global warming (IPCC, 2021). The decisive contribution of other greenhouse gases, such as CH_4 or short-lived climate forcers, was examined in this phase of Net-Zero-2050 in a qualitative manner. Being the main contributor to global warming of approximately 0.8°C in the period 2010–2019 relative to 1850–1900 (IPCC, 2021), the GHG CO_2 is responsible for about 54% of current anthropogenic climate warming (Martin et al., 2021). An alternative approach could be to include other GHGs, such as CH_4. Their relative importance may increase significantly when global CO_2 emissions are reduced to (net) zero. At around 0.5°C, CH_4 is the second highest contributor to global warming in the period 2010–2019 relative to 1850–1900 (IPCC, 2021). A common concept is to convert such gases into CO_2-equivalent emissions using the global warming potential metric. This concept is deeply embedded in climate policy but does not exist without criticism in terms of misrepresentation of the impact of short-lived climate pollutants on global temperature (Allen et al., 2018). Furthermore, CO_2 was understood as a waste product. Accordingly, CO_2 emissions were understood as "waste streams," which are treated in the hierarchy of the circular economy approach, first to avoid the emissions (i. e. by energy saving or increasing energy efficiency), second to reduce the emissions (i. e. by substituting fossil fuels by less emitting renewable fuels) and then third to remove emissions (Thrän et al., 2021; Mengis et al., 2022). All project activities considered the distinction between avoided and removed CO_2 emissions (Förster et al., 2021).

Furthermore, Net-Zero-2050 defined a carbon budget for Germany, which amounted to 6.9 Gt CO_2 from 2021 onward (Mengis et al., 2021). The remaining budget is estimated and provided, however, in CO_2 emissions only, based on a robust scientific basis of carbon budgets. In particular, the IPCC's remaining global CO_2 budget (after 2018) for a global mean near-surface air temperature change of 1.5°C (relative to the 1850–1900) ranges between 420 to 840 Gt CO_2 (67th to 33rd percentile, respectively; Rogelj et al., 2018). Newer estimates of the remaining carbon budgets with improved uncertainty constraints amount to 315 to 755 Gt CO_2 from 2018 (Matthews et al., 2021). The Net-Zero-2050 approach for allocating a carbon budget for Germany included three phases. The first phase is the convergence phase from 2021 until 2035, where German CO_2 emissions are decreased most strongly to meet their equal-per-capita share of global emissions in 2035. As of 2035, the German share of emissions is based on Germany's equal-per-capita share of global CO_2 emissions and population projections according to the 1.5°C scenario from the IPCC SR1.5 (Rogelj et al., 2018). In the last phase, Germany follows a net-zero CO_2 emissions trajectory after 2050 until 2100. In this project, it was also determined that CCS is assessed only in combination with carbon removal approaches. Storage of fossil-based carbon (i. e., fossil CO_2 emissions avoidance) was not considered a viable mitigation strategy due to the social acceptance of this option. In terms of mitigation deterrence, this combination could lead to postponing the end of using fossil fuels.

The boundary conditions presented here are only valid for the research context of the Net-Zero-2050 project. Other research projects or applications in other national contexts would need to adapt the boundary conditions for their purposes in a first step.

3.2. Inner level: The Carbon-Emission-Based System

The Carbon-Emission-Based System is based on the IPCC's categories of the Greenhouse Gas Inventory Guidelines (2006; 2019) consisting of the five main categories, (1) Energy, (2) Industrial Processes and Product Use, (3) AFOLU (Agriculture, Forestry and Other Land Use), (4) Waste, (5) Other. Net-Zero-2050 extended the system by two additional main categories: (6) Carbon Dioxide Removal (CDR), and (7) Circular Carbon Approaches. These categories were rearranged or added to the Carbon-Emissions-Based System to match the research areas and topics of Net-Zero-2050.

CO_2 removal is considered to be of crucial importance for reaching net-zero and halting anthropogenic climate change (IPCC, 2022b). In line with this, the purpose was to reflect the importance of these methods for achieving the net-zero goal. To avoid duplication and double counting, the rearranged categories were removed from their initial position in the system. If categories appear twice, e.g., forests, they either include carbon sources (category 3) or sinks (category 6). Up to our knowledge, this is the first study that puts CDR and CCU on the same level as the other categories for CO_2 emission accounting. To emphasize the significant relevance when developing net-zero strategies, these methods should not be found divided into subcategories, but listed prominently in the main categories. Each main category contains several subcategories, detailing the included processes. The system was developed for the German context, thus, the subcategories are in accordance with the prevailing circumstances in Germany. In particular, this entails that subcategories on country-specific emissions that do not apply to the German context, e. g., emissions from rice cultivation, were omitted from the system.

Transitioning the electricity system away from fossil fuels is a crucial task and inevitable to reach the carbon neutrality goal (IPCC, 2022a). The Energy category (1) encompasses emissions from Fuel Combustion Activities (1A), from Fugitive Emissions from Fuels (1B), from Heat Storage (1D) and from CO_2 Separation (1E). Thus, this category includes emissions from all energy demands and sectors and does not solely include emissions resulting from the electric energy generation sector. The two latter categories are additional subcategories that were supplemented to the categories of the IPCC's National Greenhouse Gas Inventories by Net-Zero-2050.

The category Industrial Processes and Product Use (2) covers a wide range of activities and processes, including the subcategories Mineral Industry (2A), the Chemical Industry (2B), the Metal Industry (2C), Non-Energy Products from Fuels and Solvent Use (2D), the Electronics Industry (2E), Product Uses as Substitutes for Ozone Depleting Substances (2F) and Other Product Manufacture and Use (2G). On account of the still small range of technological options, several countries emphasize the challenge that this sector constitutes, which is why it is also referred to as a "hard-to-treat" sector, and its emissions are often referred to as "hard-to-abate" (CCC, 2019; Government of Costa Rica, 2019; Republic of Portugal, 2019).

Being particularly affected by climate change impacts and providing opportunity for source-to-sink transitions, the Agriculture, Forestry and Other Land Use (AFOLU) (3) sector is one of the major components to be included to achieve the decarbonisation target (UBA—Umweltbundesamt, 2021). This category consists of the five subcategories Livestock (3A), Land (3B), Aggregate Sources on Land (3C), Harvested Wood Products (3D) and Marine (3E). Existing natural carbon sinks like existing forests are not included in the portfolio because the system focuses on anthropogenic carbon sources and sinks, again following the best scientific reasoning (Matthews et al., 2009; Rogelj et al., 2018).

The category Waste (4) covers emissions of CO_2 from Solid Waste Disposal (4A), Biological Treatment of Solid Waste (4B), Incineration and Open Burning of Waste (4C) and Emissions from Wastewater Treatment and Discharge (4D). The primary GHG emitted in this sector is methane (CH_4), however, this category needs special scrutiny when non-CO_2 GHG trends are being assessed.

The category Other (5), as specified in the IPCC Guidelines is intended to indicate all emissions and sinks that do not fall into the categories described above (IPCC, 2019a). Since Net-Zero-2050 did not want to change the IPCC's numbering, we kept the category as is and continued to extend the framework subsequently.

Due to the wide range of Carbon Dioxide Removal (CDR) (6) approaches and the corresponding research focus of the project, Net-Zero-2050 established this additional category based on scientific findings, as described in Section 2.2. Category 6 summarizes all processes, activities and mechanisms that remove CO_2 from the atmosphere and store it in the terrestrial, marine or geological reservoirs, constituting key options for removing residual CO_2 emissions. Anthropogenic carbon sinks are now mainly included in category 6 (and partly in category 3). In the final version of the Carbon-Emission-Based System, which was adjusted and finalized during the fifth step of the system composition, the subcategories of category 6 were classified by type of CO_2 capture process. Specifically, the distinction was made between biological or eco-system based carbon capture, chemical CO_2 capture options, and options that employ first biological carbon capture, which is followed by chemical point source carbon capture ("hybrid options") (see Figure 2). Hence, the main subcategories are Chemical Carbon Dioxide Removal (6A), Biological/Chemical Carbon Dioxide Removal (6B) and Biological Carbon Dioxide Removal (6C).

Since the Carbon-Emission-Based System is, as described earlier, a "living document," there are several classification possibilities. At the beginning of the project (see chapter 2.2), the CO_2 removal options were categorized according to the CO_2 storage location: Carbon Storage in the Geological Reservoir—Technological CDR, Carbon Storage in the Terrestrial Reservoir, Carbon Storage in the Marine Reservoir. This first classification corresponded to the structure of the Net-Zero-2050 project and its sub-projects. During the running time of the project and the intensive internal discussions, the classification changed toward the focus on the act of CO_2 removal. In the future, other divisions may also be appropriate.

It is important to highlight that Net-Zero-2050 made a distinction between measures that contribute to negative emissions (see Figure 2, category 6) and measures for the circular use of carbon (see Figure 2, category 7), i. e. the difference between carbon dioxide removal (CDR) and carbon capture and utilization (CCU). Thus, the category Circular Carbon Approaches (7) was also added to the categories of the IPCC's National Greenhouse Gas Inventories by Net-Zero-2050. Transport of CO_2 (7A) covers carbon emissions that result from transporting CO_2, a process that can be part of carbon dioxide removal as well as circular carbon approaches. The subcategory Carbon Capture and Utilization (7B) covers several methods, which are divided by CO_2 emission source. The term carbon dioxide capture and utilization (CCU) describes the process of CO_2 capture and subsequent use to produce valuable, new products (IPCC, 2018b). CCU can also be used in Other Industries (7B3), e. g., in the mineral industry. In addition, the category Source independent CCU (7B4) includes activities where the CO_2 emission source is not decisive for the application of the method or refers to direct air carbon capture and use (and to methods that are not covered by the aforementioned categories).

As all components of the Carbon-Emission-Based System need to be considered, it is important to disclose when expertise is available or where research gaps exist. Thus, the Carbon-Emission-Based System was the backbone of a gap analysis carried out to identify all research topics of the involved Net-Zero-2050 project partners that are connected to net-zero research fields (Köhnke et al., 2020). This way it became apparent that the project consortium had expertise to assess major parts of the emissions of Germany. Simultaneously, all project partners were consulted to identify potential partners for future collaboration. On these grounds, it is promoted to apply the Carbon-Emission-Based System within the context of a project or similar as a first step to investigate carbon neutrality strategies.

With regard to applying the Carbon-Emission-Based System on a national level, the context of the LT-LEDS guidelines and requirements was investigated. The Paris Agreement creates a framework for making voluntary pledges that can be compared and reviewed internationally, with the aim of increasing global ambition through a process of "naming and shaming" (Falkner, 2016). This means that—besides overriding distributional aspects in relation to the remaining global CO_2 budget (IPCC, 2021)—there is no internationally agreed unitarian system or benchmark set of criteria given to formulate and assess climate mitigation measures or strategies that could be considered binding on all nations. As a result, the range of criteria within the LT-LEDS submitted so far is rather heterogeneous. LT-LEDS often reflect numerous special requirements and challenges to be addressed depending on the countries' structural prerequisites and needs with regard to climate action. Thus, the Paris Agreement's bottom-up principles of climate diplomacy are based on international negotiation and cooperation instead of obligation and enforcement.

This is also reflected in the bottom-up process of LT-LEDS formulation and official submission: For Net-Zero-2050, 17 LT-LEDS have been analyzed in a first step for this system definition in the Net-Zero-2050 framework (i. e., LT-LEDS submitted to UNFCCC by 28 February 2020). Criteria such as sector and carbon budget definitions, base years for the definition of GHG reduction pathways, stakeholder engagement and behavioral change, for instance, and their individual focus and weighting differ between each LT-LEDS to a partly considerable extend (Net-Zero-2050 Team, 2021). Moreover, there is no LT-LEDS submitted so far that takes all elements of the Carbon-Emission-Based System into account. According to the UNFCCC roadmap analysis visualized in the Net-Zero-2050 web atlas (Net-Zero-2050 Team, 2021), at least one element is missing in

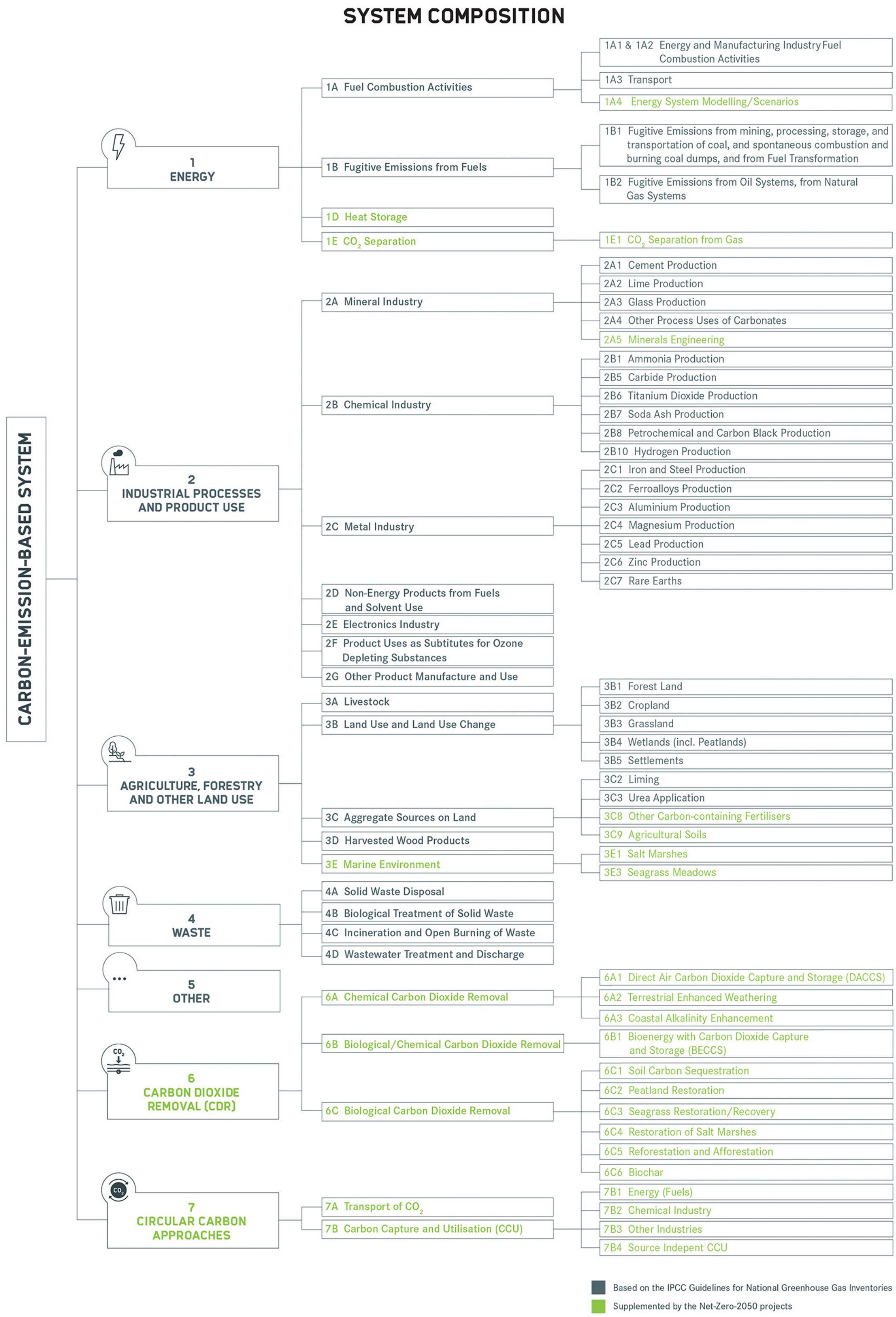

FIGURE 2
Composition of the Net-Zero-2050 Carbon-Emission-Based System. The categories of the Carbon-Emission-Based System are divided into seven main categories with associated subcategories. Categories highlighted in gray are based on the IPCC's categories and elements (2006, 2019). Categories marked in green were added or restructured and supplemented by Net-Zero-2050: The categories on CO_2 removal and circular carbon approaches (6 and 7) were rearranged or added as main categories incl. subcategories.

each LT-LEDS. In view of this, there is a need for globally uniform standards for both the formulation and evaluation of LT-LEDS, in particular from the systemic point of view. This is followed by the question of whether and to what extent this uniform evaluation will then allow an appropriate comparison of national climate mitigation strategies.

In response, Net-Zero-2050 developed the comprehensive and flexible Carbon-Emission-Based System. It must be adapted appropriately when applied to the given national structures and potentials. Despite these country-specific adjustments, a general, international application of the Carbon-Emission-Based System would allow national strategies to be compared and evaluated more effectively. Furthermore, by means of this system, carbon emissions can be allocated comprehensively and unambiguously. The respective measures and national strategies for their reduction, which can be derived from this process, can be developed in a subsequent step.

3.3. Outer level: The Framing System

Implementation of CDR options faces challenges and hurdles that are individual to the specific option and include aspects such as technical feasibility, economic viability as well as concerns related to environmental impacts and public acceptance. Hence systemic changes are needed that not only address public policies but also societal acceptance (de Coninck et al., 2018; IPCC, 2022a). Accelerating the deployment of CDR options is, thus, contingent on the feasibility of CDR options and the costs and impacts public and private actors are willing to accept. Thereby it is critical to identify options for removing or at least reducing barriers across multiple dimensions as well as on establishing and enhancing conditions for implementation (IPCC, 2022a). To assess the feasibility of these options, SR1.5 proposes—based on research from IPCC's Fifth Assessment Report (AR5)—taking into account six different feasibility options: economic, technological, institutional, socio-cultural, environmental/ecological and, lastly, geophysical (de Coninck et al., 2018, p. 380).

Net-Zero-2050 focused on the feasibility of CDR to address the research gap concerning CDR options. In line with this, the aim was to provide a systemic view on CDR deployment with the goal of supporting the implementation of the national climate strategy of achieving net-zero emissions. The multi-dimensional approach aims at addressing the relevant actors—this is of great importance, as the transformation to a net-zero Germany requires the consideration of all stakeholders and their coordinated, purposeful involvement. The Framing System is connected to the underlying system boundaries and interacts with the subsequent Carbon-Emission-Based System.

As indicated in the previous chapter, the research carried out by de Coninck et al. (2018) formed the basis for the project's outer level called the Framing System. Following internal discussions and recommendations from external experts, the project's feasibility dimensions were slightly adapted compared to the ones of the IPCC (see Figure 3). As a result, the following five dimensions have been considered in the Framing System:

- Economic dimension, for example, to assess cost effectiveness or productivity enhancement potential.

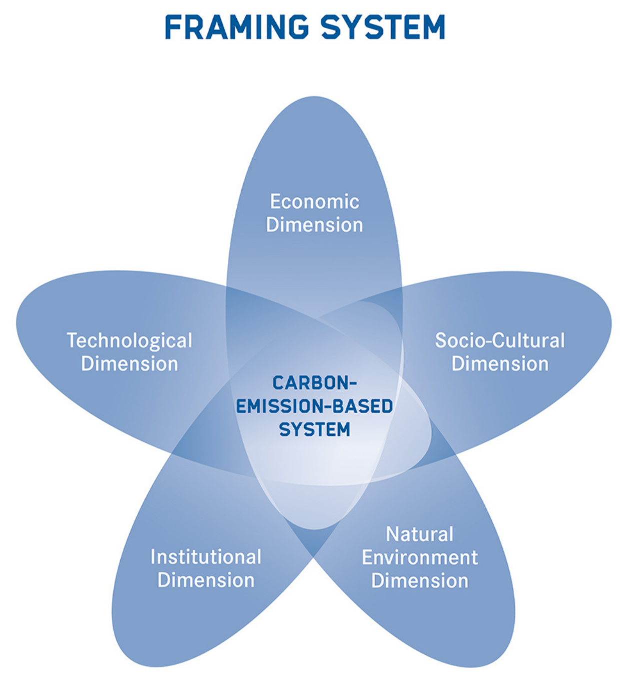

FIGURE 3
The dimensions of the Net-Zero-2050 Framing System.

- Technological dimension, for example, to assess technical scalability and the readiness level of CDR technologies.
- Institutional dimension, for example, to assess political acceptability as well as legal and administrative feasibility.
- Socio-cultural dimension, for example, to assess intergenerational equity as well as social challenges or co-benefits (i. e., health, education).
- Natural environment dimension, for example, to assess impacts on land use, biodiversity, soil and water quality.

The last dimension listed here combines the two dimensions mentioned in SR1.5, environmental/ecological and geophysical. Additionally, in all five dimensions the time aspect must be considered as it is one of the most important features concerning CDR deployment. On the one hand, the amount of CDR needed will depend on the progress in reducing and avoiding emissions. On the other hand, the delayed response of the climate system to mitigation efforts due to its inertia and internal variability should also be taken into account (Samset et al., 2020). Another time-critical aspect of CDR is the permanence of CO_2 storage, which varies for different CDR options (e. g., biological vs. geological storage) and is a key to reaching net-zero.

In particular, regarding the readiness of CDR options, many of the techniques for removing CO_2 from the atmosphere are unproven at large scale and some promising CDR options still await testing in the deployment environment at pilot sites (Fuss et al., 2018, 2021). The scale of deployment of particular CDR options is widely discussed in the literature and may be shaped by many factors, e. g., their ability to provide appropriate capture and storage potentials, their technical integration within sociotechnical systems, their acceptance by different stakeholders as well as juridical and market compatibilities (Fridahl et al., 2020). Currently, the necessity of CDR deployment is widely acknowledged (e. g., IPCC, 2022a) and key questions around CO_2 removal explored in research should therefore address the following aspects: Which CDR options, and in what ways, could be deployed? At what scale and by when should it happen? What actors should be involved in this process? How should the public be involved and have a say as governments develop policies for scaling up CO_2 removal? What are the potential benefits and risks? What are the effects on the environment? The Framing System consolidates these types of questions by assigning them to the above mentioned dimensions.

Considering specifically the evaluation of feasibility of CO_2 removal technologies, two tools have been developed in the Net-Zero-2050 project: So-called "model concepts" of CDR options (Borchers et al., 2022) and a comprehensive CDR assessment framework (Förster et al., 2022). The CDR assessment framework has been built upon the previous feasibility assessment of bioenergy strategies in Germany (Thrän et al., 2020). It provides a set of criteria and indicators grouped into six dimensions (environmental, technological, economic, social, institutional and systemic) through which the CDR options can be assessed and compared within an assessment matrix. Besides the qualitative and quantitative assessment of indicators for the feasibility of CDR options, the framework has been equipped with a traffic light system in which the results of the feasibility assessment are also presented through a color-coded system (red-yellow-green). The colors indicate what effort (high, medium, little to no) is needed to overcome hurdles for the deployment of a particular CDR option.

In line with this, the model concepts were developed for assessing the CDR options using the CDR assessment framework. There is an extensive amount of information on CDR options available today (e. g., Minx et al., 2018). The options are investigated at different scales and from different perspectives (e. g., technical, socio-economic, policy-oriented, etc.). For their deployment, however, it is important to put this information into context, considering the national and regional conditions applicable/effective on the site of implementation (e. g., geophysical, resource potentials, existing infrastructure, etc.). Therefore, based on a literature review and experts' knowledge, for each analyzed CDR option a dedicated implementation example was created, a CDR model concept, which helped to visualize how their deployment in the real world could look like. Information on CDR model concepts has been gathered in tabular factsheets with a unified set of indicators describing general concept characteristics (e. g., its maturity level, energy concept, infrastructure, biophysical conditions, location), its input requirements, output, environmental impacts, economic and systemic parameters. This approach facilitated the preparation of a coherent description across different CDR options, but also the starting point to assess the national and regional potentials.

Thus, the Framing System addresses and fosters the implementation of CDR and other strategies to reach net-zero. Beyond this and with regard to the further development of the Framing System, CDR options as a climate mitigation strategy must be considered in the context of climate adaptation. Hence, mitigation and adaptation are highly interdependent and the synergies between both are crucial: without sufficient climate mitigation, the ability to adapt to existing or future climate changes will be lost. Consequently, it would be impossible to adapt both natural and anthropogenic systems to all levels of global warming (IPCC, 2022b).

4. Concluding remarks

There is no scientific doubt that climate change is caused by human activities (IPCC, 2021). However, there is still a need to examine the options and mechanisms for mitigating the causes, which includes mechanisms for reducing carbon emissions as well as removing carbon dioxide from the atmosphere to achieve proclaimed net-zero goals. Contributing to this, the interdisciplinary team of 80 scientists carried out research in the Net-Zero-2050 project on the topic how Germany can reach carbon neutrality by 2050. As a basis for all activities in this project, the Net-Zero-2050 System was developed. In addition to that, the lack of a unified systems approach for preparing the LT-LEDS on how to achieve carbon neutrality, as agreed in the Paris Agreement, was identified. The LT-LEDS submitted to date differ considerably in terms of structure and scope, to an extent that they are not comparable. Net-Zero-2050 addresses this issue by presenting and discussing a comprehensive system. The Net-Zero-2050 System can be used in different contexts and may guide other projects or authorities developing national strategies to achieve carbon neutrality.

Net-Zero-2050 identified three central areas of application. First, in the project context the Net-Zero-2050 System can be used as a starting point for approaching the target of creating or contributing to national net-zero strategies. On a national level, it can be applied for reviewing the current system for national inventory reporting. The proposed system provides a basis for creating long-term strategies to achieve carbon neutrality on a national level. Net-Zero-2050 proposes to use the system beyond the context of projects. If the various countries would use this systems approach, it would facilitate the comparability of the different, national strategies. The multiple application options of the Carbon-Emission-Based System combined with the System Boundaries and of the Framing System underline the universal applicability of the three parts of the Net-Zero-2050 System. The System Boundaries defined here are context-specific for Germany. If the System Boundaries are to be applied in similar contexts for other countries, they have to be adapted accordingly and in line with the country-specific conditions. The Carbon-Emission-Based System approach can be used for different purposes at different levels. The categories of the Carbon-Emission-Based System presented here apply to Germany and are thus—in line with the System Boundaries—context-specific. They have to be adapted and, if necessary, extended depending on the context and the circumstances of the country. The dimensions of the Framing System apply universally. They provide an initial overview of the framework to be considered with regard to implementation of carbon neutrality strategies and do not need to be adapted depending on the context.

The individual parts of the Net-Zero-2050 System can be used independently, however in a subsequent step the system must be considered in its entirety. The combination of all three system parts allows a holistic view with regard to achieving carbon neutrality.

Data availability statement

For the scientific data that support the findings of this work, we refer to the website of the Net-Zero 2050 project https://netto-null.org/. The list of LT-LEDs cited in the paper is provided in a spreadsheet in the Supporting Information.

Ethics statement

Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

FK, BS, JE, MB, JF, DT, NM, AO, and DJ contributed to conception and design of the article. FK led the drafting of the manuscript with contributions from all co-authors. BS, JE, KG, MB, JF, DT, and NM wrote sections of the manuscript. FK, BS, and NM conceived of and created Figure 1, FK and BS developed Figure 2, and FK, JE, and BS created Figure 3. All authors contributed to manuscript revision, read, and approved the submitted version.

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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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2023.1056023/full#supplementary-material

References

Allen, M. R., Shine, K. P., Fuglestvedt, J. S., Millar, R. J., Cain, M., Frame, D. J., et al. (2018). A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *NPJ Clim. Atmosph. Sci.* 1, 1–8. doi: 10.1038/s41612-018-0026-8

BDI and BCG—Bundesverbands der Deutschen Industrie and Boston Consulting Group (2021). *Studie "Klimapfade 2.0—Ein Wirtschaftsprogramm für Klima und Zukunft" im Auftrag des Bundesverbands der deutschen Industrie e.V. und der Strategieberatung BCG*. Available online at: https://issuu.com/bdi-berlin/docs/211021_bdi_klimapfade_2.0_-_gesamtstudie_-_vorabve (accessed September 01, 2022).

BMUB—Federal Ministry for the Environment Nature Conservation Building and Nuclear Safety (2016). *Climate Action Plan 2050: Principles and Goals of the German Government's Climate Policy*. Berlin: BMUB. Available online at: https://unfccc.int/sites/default/files/resource/Klimaschutzplan_2050_eng_bf.pdf (accessed September 01, 2022).

Borchers, M., Thrän, D., Chi, Y., Dahmen, N., Dittmeyer, R., Dolch, T., et al. (2022). Scoping carbon dioxide removal options for Germany: What is their potential contribution to Net-Zero CO_2? *Front. Clim.* 4, 343. doi: 10.3389/fclim.2022.810343

Buylova, A., Fridahl, M., Nasiritousi, N., and Reischl, G. (2021). Cancel (out) emissions? The envisaged role of carbon dioxide removal technologies in long-term national climate strategies. *Front. Clim.* 3, 675499. doi: 10.3389/fclim.2021.675499

CAT—Climate Action Tracker (2021). *Germany*. Bonn: CAT—Climate Action Tracker. Available online at: https://climateactiontracker.org/countries/germany/ (accessed September 01, 2022).

CCC—Committee on Climate Change (2019). *Net Zero—The UK's Contribution to Stopping Global Warming*. Philippines: CCC—Committee on Climate Chang. Available online at: https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf (accessed September 01, 2022).

de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., et al. (2018). "Strengthening and implementing the global response," in *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, eds V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, et al. Available online at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_Low_Res.pdf (accessed September 01, 2022).

Dena—Deutsche Energie-Agentur GmbH (2021). *Dena-Leitstudie Aufbruch Klimaneutralität*. Available online at: https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/Abschlussbericht_dena-Leitstudie_Aufbruch_Klimaneutralitaet.pdf (accessed September 01, 2022).

Falkner, R. (2016). The Paris agreement and the new logic of international climate politics. *Int. Affairs* 92, 12708. doi: 10.1111/1468-2346.12708

Förster, J., Beck, S., Borchers, M., Gawel, E., Korte, K., Markus, T., et al. (2022). Framework for assessing the feasibility of carbon dioxide removal options within the national context of Germany. *Front. Clim.* 4, 25. doi: 10.3389/fclim.2022.758628

Förster, J., Mengis, N., Schill, E., Xiao, M., and Thrän, D. (2021). *Project Briefing #3. Avoided and Removed Emissions*. Available online at: https://www.netto-null.org/imperia/md/assets/net_zero/dokumente/3_CO2_2021_10_web.pdf (accessed September 01, 2022).

Fridahl, M., Hansson, A., and Haikola, S. (2020). Towards indicators for a negative emission climate stabilization index: problems and prospects. *Climate* 8, 75. doi: 10.3390/cli8060075

Fuss, S., Gruner, F., Hilaire, J., Kalkuhl, M., Knapp, J., Lamb, W., et al. (2021). *CO_2-Entnahmen: Notwendigkeit und Regulierungsoptionen. Studie im Auftrag der Wissenschaftsplattform Klimaschutz.* Berlin: WPKS. Available online at: https://www.wissenschaftsplattform-klimaschutz.de/files/WPKS_Gutachten_MCC_PIK.pdf (accessed August 13, 2022).

Fuss, S., Lamb, W. F., and Callaghan, M. W. (2018). Negative emissions—Part 2: costs, potentials and side effects. *Environ. Res. Lett.* 13, 9326. doi: 10.1088/1748-9326/aabf9f

GermanZero (2020). *Unser Fahrplan für ein klimaneutrales Deutschland.* Available online at: https://klimaentscheid-lichtenfels.de/wp-content/uploads/2021/04/5ece7812eb97a0be582bad67_Der-15-Grad-Klimaplan-fuer-Deutschland.pdf (accessed September 01, 2022).

Government of Costa Rica (2019). *National Decarbonization Plan Costa Rica 2018–2050.* Available online at: https://unfccc.int/sites/default/files/resource/NationalDecarbonizationPlan.pdf (accessed September 01, 2022).

IPCC—Intergovernmental Panel on Climate Change (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*, eds H. S. Eggleston, L. Buendia, K. Miwa, et al. (Pigeon Forge: IGES). Available online at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (accessed September 01, 2022).

IPCC—Intergovernmental Panel on Climate Change (2018b). "Annex I: Glossary [Matthews, J.B.R. (ed.)]," in *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, eds V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, et al. (Cambridge: Cambridge University Press,), 541–562.

IPCC—Intergovernmental Panel on Climate Change (2019a). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, eds E. Calvo Buendia, K. Tanabe, A. Kranjc, et al. (Switzerland: IPCC). Available online at: https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html (accessed September, 01, 2022).

IPCC—Intergovernmental Panel on Climate Change (2019b). *Terms of Reference for the Production of a Methodology Report to Refine the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Available online at: https://www.ipcc.ch/site/assets/uploads/2021/09/l3_adopted_outline_methodology_report_guideline.pdf (accessed September 01, 2022).

IPCC—Intergovernmental Panel on Climate Change (2021). "Summary for policymakers," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, eds V. Masson-Delmotte, P. Zhai, A. Pirani, et al. (Cambridge: Cambridge University Press), 3–32. Available online at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf (accessed September, 01, 2022).

IPCC—Intergovernmental Panel on Climate Change (2022a). *Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Available online at: https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf (accessed September 01, 2022).

IPCC—Intergovernmental Panel on Climate Change (2022b). *Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Available online at: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FinalDraft_FullReport.pdf (accessed September 01, 2022).

IPCC-Intergovernmental Panel on Climate Change. (2018a). "Global warming of 1.5○C," in *An IPCC Special Report on the Impacts of Global Warming of 1.5 C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, eds V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (Cambridge; New York, NY: Cambridge University Press). doi: 10.1017/9781009157940

Köhnke, F., Görl, K., Mengis, N., Preuschmann, S., Blome, T., Steuri, B., et al. (2020). *System Definition and Integration of Key Actors [Part 1] [Version 1].* Hamburg: Climate Service Center Germany (GERICS) (Internal project report).

Kopernikus-Projekt Ariadne. (2021). *Ariadne-Report-Deutschland auf dem Weg zur Klimaneutralität 2045-Szenarien und Pfade im Modellvergleich.* Potsdam: Kopernikus-Projekt Ariadne, Potsdam-Institut für Klimafolgenforschung. doi: 10.48485/pik.2021.006

Martin, M. A., Sendra, O. A., Bastos, A., Bauer, N., Bertram, C., Blenckner, T., et al. (2021). Ten new insights in climate science 2021: a horizon scan. *Global Sustain.* 91, 244. doi: 10.1017/sus.2021.25

Matthews, H. D., Gillett, N., Stott, P., and Zickfeld, K. (2009). The proportionality of global warming to cumulative carbon emissions. *Nature* 459, 829–832. doi: 10.1038/nature08047

Matthews, H. D., Tokarska, K. B., Rogelj, J., Smith, C. J., MacDougall, A. H., and Haustein, K., et al. (2021). An integrated approach to quantifying uncertainties in the remaining carbon budget. Commun. *Earth Environ.* 2, 64. doi: 10.1038/s43247-020-00064-9

Mengis, N., Kalhori, A., Simon, S., Harpprecht, C., Baetcke, L., Prats-Salvado, E., et al. (2022). Net-zero CO_2 Germany—a retrospect from the year 2050. *Earth's Fut.* 10, 2324. doi: 10.1029/2021EF002324

Mengis, N., Simon, S., Thoni, T., Stevenson, A., Goerl, K., Steuri, B., et al. (2021). *Project Briefing #2. Defining the German Carbon Budget.* Available online at: https://www.netto-null.org/imperia/md/assets/net_zero/dokumente/2_carbonbudget_2021_10_web.pdf (accessed September 01, 2022).

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., et al. (2018). Negative emissions—Part 1: research landscape and synthesis. *Environ. Res. Lett.* 13, 9326. doi: 10.1088/1748-9326/aabf9b

Net-Zero-2050 Team (2021). *Net Zero 2050 Web Atlas.* Available online at: https://atlas.netto-null.org/roadmaps (accessed September 01, 2022).

Prognos, Öko-Institut, Wuppertal-Institut (2021). *Klimaneutrales Deutschland 2045. Wie Deutschland Seine Klimaziele Schon Vor 2050 Erreichen Kann.* Available online at: https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_04_KNDE45/A-EW_209_KNDE2045_Zusammenfassung_DE_WEB.pdf (accessed September 01, 2022).

Republic of Portugal (2019). *Roadmap for Carbon Neutrality by 2050 (RNC 2050)—Long-Term Strategy for Carbon Neutrality of the Portuguese Economy by 2050.* Available online at: https://unfccc.int/documents/200175 (accessed September 01, 2022).

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., et al. (2018). "Mitigation pathways compatible with 1.5°C in the context of sustainable development," in *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, eds V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, et al. Available online at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf (accessed September 01, 2022).

Samset, B. H., Fuglestvedt, J. S., and Lund, M. T. (2020). Delayed emergence of a global temperature response after emission mitigation. *Nat. Commun.* 11, 3261. doi: 10.1038/s41467-020-17001-1

Sensfuß, F., Lux, B., Bernath, C., Kiefer, C., Pfluger, B., Kleinschmitt, C., et al. (2021). *Langfristszenarien für die Transformation des Energiesystems in Deutschland 3 – Kurzbericht: 3 Hauptszenarien.* Available online at: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccx/2021/LFS_Kurzbericht.pdf (accessed September 01, 2022).

Simon, S., Xiao, M., Harpprecht, C., Sasanpour, S., Gardian, H., and Pregger, T. (2022). A pathway for the German energy sector compatible with a 1.5°C carbon budget. *Sustainability* 14, 25. doi: 10.3390/su14021025

Thoni, T., Beck, S., Borchers, M., Förster, J., Görl, K., Hahn, A., et al. (2020). Deployment of negative emissions technologies at the national level: a need for holistic feasibility assessments. *Front. Clim.* 2, 590305. doi: 10.3389/fclim.2020.590305

Thrän, D., Bauschmann, M., Dahmen, N., Erlach, B., Heinbach, K., Hirschl, B., et al. (2020). Bioenergy beyond the German "Energiewende": assessment framework for integrated bioenergy strategies. *Biomass Bioenergy.* 142, 105769. doi: 10.1016/j.biombioe.2020.105769

Thrän, D., Mengis, N., Mayer, M., Steuri, B., Oschlies, A., Simon, S., et al. (2021). *Project Briefing #1. Structure of Project 1 within the Cluster | Net-Zero-2050.* Available online at: https://www.netto-null.org/imperia/md/assets/net_zero/dokumente/1_p1-structure_2021_10_web.pdf (accessed September, 01, 2022).

UBA—Umweltbundesamt (2019). *Wege in eine ressourcenschonende Treibhausgasneutralität RESCUE – Studie.* Available online at: https://www.umweltbundesamt.de/themen/klima-energie/klimaschutz-energiepolitik-in-deutschland/szenarien-konzepte-fuer-die-klimaschutz/rescue-wege-in-eine-ressourcenschonende#hintergrund (accessed September 01, 2022).

UBA—Umweltbundesamt (2021). *Treibhausgasminderung um 70 Prozent bis 2030: So kann es gehen!* Available online at: https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/21_12_29_uba_pos_treibhausgasminderung_um_70prozent_bf.pdf (accessed September 01, 2022).

UNFCCC—United Nations Framework Convention on Climate Change (2022a). *The Paris Agreement.* Available online at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed September 01, 2022).

UNFCCC—United Nations Framework Convention on Climate Change (2022b). *Communication of Long-Term Strategies.* Available online at: https://unfccc.int/process/the-paris-agreement/long-term-strategies (accessed September 01, 2022).

UNFCCC—United Nations Framework Convention on Climate Change (2022c). *Greenhouse Gas Inventory Data: Detailed data by Party.* Available online at: https://di.unfccc.int/detailed_data_by_party (accessed September 01, 2022).