



PROJECT REPORT 2025

PHASE II

Contents

3	INTRODUCTION
	From Roadmap to Reality – Shaping Climate Solutions Through Systemic Research
4	Structure and Focus Areas of the Helmholtz Climate Initiative (2019–2024)
7	CLUSTER I: NET-ZERO-2050 (MITIGATION)
8	Overview
11	Project 1
	Reality Check of Actions for a Carbon-Neutral Germany by 2050
28	Project 2
	Technological Options for Carbon Capture Utilization and Storage
42	Project 3
	Peatland Rewetting as a Natural Climate Solution (Part I, Aspects Mitigation)
50	CLUSTER II: ADAPTATION
51	Introduction
54	Counterfactual scenarios and large-scale weather regimes for extreme rainfall events over Germany
61	Future scenarios through jet stream nudging
67	Toward a High-resolution Flash Flood Impact-based Forecasting in Germany – Proof of Concept
79	Heat-vulnerable populations, the effects of heat on health in Germany, and approaches for better heat adaptation and resilience
84	Operationalization of a Generalized Health Model for Heat Stress
89	CLUSTER III: COMMUNICATION

From Roadmap to Reality – Shaping Climate Solutions Through Systemic Research

The challenges posed by climate change are more pressing than ever – evidenced not only by the extreme weather events of recent years, but also by the growing societal and political debate on pathways toward a climate-neutral future. With the Helmholtz Climate Initiative, the Helmholtz Association established a comprehensive research framework in 2019 to provide science-based contributions to climate mitigation and adaptation.

Following a successful first phase, in which key courses of action were identified and scientifically developed, the second phase focused on critically reflecting on these options from multiple perspectives. In close collaboration with stakeholders from politics, public administration, industry, and civil society, selected measures underwent a “reality check” to assess their feasibility and impact. The resulting findings further refined the proposed measures and improved their practicability and effectiveness.

The initiative’s work was organized in three interdisciplinary clusters addressing mitigation, adaptation, and communication. A detailed overview of the initiative’s structure and research focus areas is provided in the following section.

This project report documents the central results of the second phase of the Helmholtz Climate Initiative. It not only highlights what has been achieved, but also outlines what must follow to turn knowledge into long-term impact. Only then can we meet the complexity of climate change – and develop viable answers for the future.

Structure and Focus Areas of the Helmholtz Climate Initiative (2019–2024)

The Helmholtz Climate Initiative (2019 to 2024)

Climate research is a key focus of the Helmholtz Association. To consolidate this expertise and make it available as well-founded and comprehensible knowledge, the Helmholtz Climate Initiative (HI-CAM) was launched in 2019.

Completed Projects

As part of the initiative, researchers from 15 Helmholtz Centers jointly developed strategies to reduce greenhouse gas emissions and adapt to unavoidable climate impacts – with a focus on Germany. The initiative concentrated on two main areas: „Net-Zero-2050“ (Cluster I, Mitigation) and „Adaptation to Extreme Events“ (Cluster II, Adaptation). The science-based clusters were complemented by a communication cluster (Cluster III, communication).

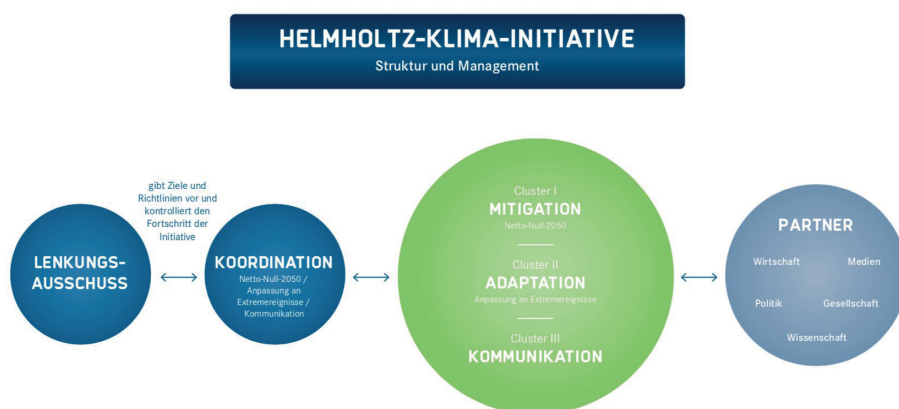


Figure 1:
Structure of the Helmholtz Climate Initiative



Figure 2:
Overview of the participating centers

Leadership and Coordination of the Helmholtz Climate Initiative

Scientific Lead of Cluster I (Mitigation):
Prof. Dr. Daniela Jacob

Scientific Coordinators of Cluster I (Mitigation):
Bettina Steuri (Phase 1)
Fiona Köhnke (Phase 2)

Scientific Lead of Cluster II (Adaptation):
Prof. Dr. Georg Teutsch (Phase 1)
Prof. Dr. Sabine Attinger (Phase 2)

Scientific Coordinator of Cluster II (Adaptation):
Dr. Andreas Marx

Head of Cluster III (Communication):
Roland Koch (Phase 1)

Cluster I: Net-Zero-2050 (Mitigation)

The „Net-Zero-2050“ research project of the Helmholtz Climate Initiative investigated scientifically sound strategies for achieving a carbon neutral Germany by 2050. It was based on the goal of limiting global temperature rise to below 2°C compared to pre-industrial levels, as outlined by the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on Global Warming of 1.5°C.

Phase I included four subprojects:

1. **Roadmap & Scenarios:** Two subprojects assessed the most promising contributions to carbon neutrality under German conditions and combined them into a pilot roadmap („Wegweiser“).
2. **Circular Carbon Use:** Approaches were explored to remove CO₂ from the atmosphere and convert it into energy carriers using renewable energy.
3. **Underground Storage Solutions:** The project analyzed the technically and economically feasible potential for energy storage from various perspectives.
4. **Nature as a Storage System:** Terrestrial and marine systems were evaluated for their potential to reduce CO₂ and store carbon under different climate scenarios.

Phase II focused on implementation and deepening:

1. **Reality Check:** Selected recommendations developed in Phase I were reviewed for practical feasibility in thematic focus groups with practitioners.
2. **Technological Carbon Approaches:** Research focused on direct electrocatalytic conversion of CO₂, hydrothermal CO₂ mineralization, and the combination of underground CO₂ storage with geothermal heat utilization.
3. **Rewetting of Peatlands:** Water availability in German peatland areas was analyzed, and a pilot project for rewetting in Potsdam was developed in collaboration with local stakeholders.

The project results were incorporated into a „Wegweiser“ (Phase I) and a „Reality Check“ (Phase II) and aimed to advance public and political debate on carbon neutrality at various levels - including within the Helmholtz Association.

Cluster II: Adaptation

The Cluster II of the Helmholtz Climate Initiative focused on changes in atmospheric and terrestrial extreme events and the development of adaptation tools.

Phase I included eight subprojects:

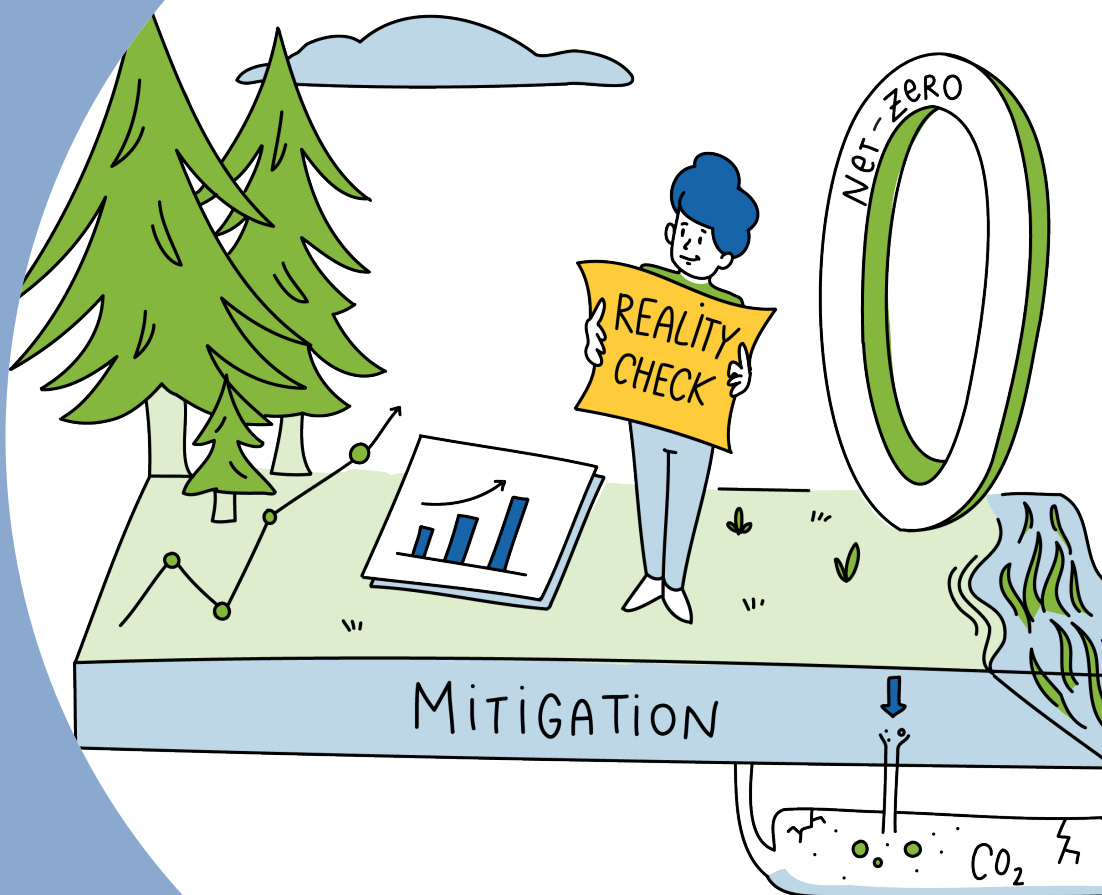
The changes of the jet stream and thus the change of extreme events have been investigated methodically at AWI, GEOMAR and KIT as well as transferred into storylines and published. A series of jet stream diagnostics were developed at GEOMAR to compare reanalysis and model data. This involved repeated 100-year AMIP-style model simulations with 2018 heat and drought conditions and scenarios of 1.5-2-3 and 4 K global warming. Through collaboration with AWI, the potential for an idealized study of two-way ocean-atmosphere interaction was identified. Extensive media work was carried out by the AWI, as well as exchanges with stakeholders (including e.g. Vattenfall). Ocean boundary data (sea surface temperatures and sea ice coverage) from transient AWI climate integrations have been used in the project “Jet streams under climate change: Time slice experiments with ICON-ART” at KIT to produce ensemble quasi-equilibrium climate simulations for certain target years that correspond to threshold warmings detected in the AWI integrations. The data allow the comprehensive estimation of probability density functions of atmospheric climatic states in a warmer world and are available to all partners.

HI-CAM generated an extensive climate impact dataset on the water budget in the first phase. A climate-hydrology reference ensemble consisting of 88 simulations under three climate scenarios was created at the UFZ, which is already being used in follow-up orders for the German Technical and Scientific Association for Gas and Water (DVGW), among others, and will thus be the reference for water supply in Germany. At FZJ, a consistent, coupled surface-groundwater climate impact simulation was also contributed. For the first time in Germany, a kilometer-scale high-resolution bias-adjusted climate ensemble was created in cooperation between GERICS and UFZ. In addition, GERICS provided the required climate data in the adaptation subprojects. Non-specialist Helmholtz scientists were advised and supported in the interpretation, possibilities and limitations of climate simulation data.

Phase II involves deepening our understanding of extreme situations and further developing adaptation tools with a focus on environmental and health systems.

Cluster III: Communication

The third cluster engaged with diverse societal groups to raise awareness and foster dialogue on the impacts, risks, and challenges of climate change. It developed coherent communication strategies and campaigns to meaningfully connect science and society. On one hand, it presented the results of the initiative and the current state of climate research within Helmholtz; on the other, it provided accessible information on climate change beyond the initiative's scope. Key outputs included factsheets, infographics, articles, and videos that made climate science understandable and relevant to a broad audience. Many of the materials and communication channels established within the cluster remain active and continue to strengthen public understanding and engagement with climate issues through the Helmholtz KLIMA Dialogue Platform.



CLUSTER I

Cluster I: Net-Zero-2050 (Mitigation)

Lead: Jacob, D.

Co-ordination: Köhnke, F.

Affiliation(s): Climate Service Center Germany (GERICS) | Helmholtz-Zentrum Hereon

OVERVIEW

In phase I of **Net-Zero-2050**, Cluster I of the Helmholtz Climate Initiative (HI-CAM), possible ways in which CO₂ could be removed from the atmosphere to compensate for residual emissions were shown. In the end, a catalog with over 120 recommendations for action on how to get carbon dioxide removal (CDR) started in Germany was compiled. The key message of all recommendations is: The short period until 2030 is crucial.

CDR approaches must be researched and tested. Furthermore, the framework conditions must be created to have these removal options ready in case they are needed. Stepping forward in terms of implementation, necessary actions need to be reflected and discussed with relevant stakeholders. Effective stakeholder participation is usually deemed important to accelerate and legitimize implementation. With a strong stakeholder involvement, Net-Zero-2050 aimed to ignite and excite a necessary political and social debate about CO₂ utilization and storage in Germany in the course of the second funding phase.

An overall goal of Net-Zero-2050 was to build a network as well as prepare demonstration and pilot projects to be set up through cooperation within the Helmholtz Association to test technologies on a larger scale. From the technological point of view, the second phase's thematic focal points were on the different technological options for carbon capture utilization and storage, and from the natural climate solutions point of view the focus was on peatlands.

Thus, the second phase of Net-Zero-2050 was built up on three projects (see Figure 1):

- **Project 1**'s core activity is the coordination, support and guidance of the interactions between the consortium's experts and the stakeholders. Furthermore, it pulls together the knowledge from Project 2 and Project 3.
- **Project 2** is the "technology-based" project. The project's topics relate to direct electrocatalytic conversion of CO₂ into fuels and chemicals and assess options and potentials of combining temporary subsurface CO₂ storage with geothermal heat harvesting.
- **Project 3** is the "natural climate solutions" project and it is dedicated to rewetting peatlands in the region of Potsdam in Brandenburg.

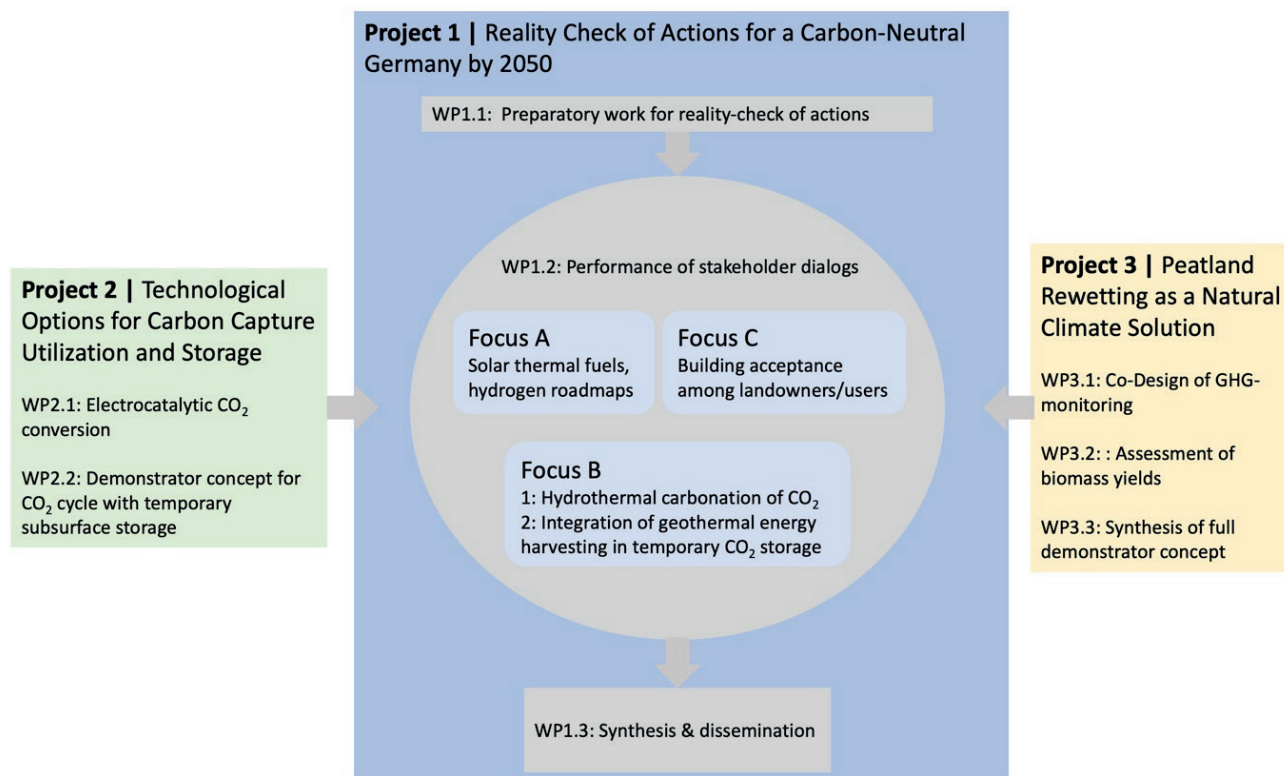


Figure 1: Net-Zero-2050's structure within the second funding phase.

INTERDISCIPLINARY COLLABORATION

The Helmholtz Association hosts an enormous variety of excellent competencies that contribute to science-based options related to the truly grand societal challenge of dealing with climate change. Therefore, Net-Zero-2050 again combined the expertise from eight Helmholtz centers and three research areas:

— Earth and Environment:

- Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon (coordinator)
- Helmholtz-Zentrum für Geoforschung (GFZ)
- Helmholtz-Zentrum für Umweltforschung (UFZ)

— Energy:

- Karlsruher Institut für Technologie (KIT)
- Deutsches Zentrum für Luft- und Raumfahrt (DLR)
- Helmholtz-Zentrum Dresden-Rossendorf (HZDR)
- Helmholtz-Zentrum Berlin (HZB)
- Forschungszentrum Jülich (FZJ)

— Information and Data Science:

- Helmholtz-Zentrum Hereon

The expertise of multiple non-academic stakeholders was specifically included in projects 1 and 3 of phase II.

In order to make the best possible use of interdisciplinary teamwork, proven dialog formats of the first funding phase were adopted in an adapted manner for the second funding phase. These include:

- Annual full-day workshops with the entire team, parts with the practice partners if necessary. The workshops are to be conducted online, hybrid, or on-site as appropriate.
- Regular Jour Fixe with the PIs and partially with the entire team to discuss strategic questions.

Launch of the "Net-Zero Network"

As part of the second project phase, all partners involved have jointly decided that the successful collaboration should continue beyond the official funding period. The "Net-Zero Network" was thus established with the aim of continuing to promote scientific dialogue on negative emissions, CO₂-neutrality and climate resilience. While the consortium of the project formed the first members, the network was then opened up to all interested parties from science and practice.

CLUSTER I: NET-ZERO-2050 PHASE II

Project 1

Reality Check of Actions for a Carbon-Neutral Germany by 2050

AUTHORS

**Climate Service Center
Germany (GERICS) |
Helmholtz-Zentrum Hereon**

Daniela Jacob
Fiona Köhnke
Bettina Steuri

**Karlsruhe Institute of
Technology (KIT)**

Katharina Schätzler
Florian Bauer
Judith Bremer
Jerome Azzola

**German Aerospace Center
(DLR), Institute of Future
Fuels ^a and Institute of
Networked Energy Systems ^b**

Enric Prats-Salvado ^a
Nathalie Monnerie ^a
Thomas Pregger ^b
Stefan Kronshage ^b
Robin König ^b

**Helmholtz-Zentrum Potsdam
Deutsches
GeoForschungsZentrum (GFZ)**
Torsten Sachs

**Jülich Systems Analysis,
Forschungszentrum Jülich (FZJ)**
Imke Rhoden

Helmholtz-Zentrum Hereon
Torsten Brinkmann

**Helmholtz-Zentrum Berlin für
Materialien und Energie (HZB)**
Björn Rau

**Helmholtz-Zentrum
Dresden-Rossendorf (HZDR)**
Stefan Fogel

Centers involved:



SUMMARY

One of the main goals of Net-Zero-2050, Cluster I of the Helmholtz Climate Initiative, was to carry forward climate research within the Helmholtz Association. In phase 1, Net-Zero-2050 concentrated on the topic of CO₂ neutrality with the key question: How do we restructure the energy system and how do we deal with emissions that are difficult to avoid? The ten participating Helmholtz centers conducted interdisciplinary research across five research areas, compiling and synthesizing their findings. The main result was a guide (*Netto-Null-2050 Wegweiser*) with over 100 technology-based and decision-supporting recommendations for action for a CO₂-neutral Germany by the middle of the century. In this second phase of Net-Zero-2050, which ran from March 2023 until the end of 2024, eight Helmholtz centers were involved. The focus here was set on a reality check of the project's research results with practitioners and stakeholders. Moreover, a **Net-Zero Network** between actors and stakeholders from research and practice was established. Additionally, Net-Zero-2050 organized the Net-Zero-2050 Summer School, which offered young scientists from the Helmholtz Association detailed insights into transdisciplinary research on a carbon-neutral society.

ACHIEVED RESULTS

W.P 1.1: Preparatory work for “Reality-Check” of actions

Compilation of recommendations for action of the *Netto-Null-2050 Wegweiser* [1] and concept for each stakeholder interaction format

On the basis of their expertise and practical experience, ten key experts were selected as interview partners for the “reality-check” of actions. The “reality-check” serves as an approach to check the relevance, feasibility, and implementation potential of the recommendations for action. To account for the multitude of different recommendations of actions, in a first step, focus groups combining similar recommendations have been created. For each of the focus groups, selected stakeholders and experts from industry and research have been chosen by Net-Zero experts to deliver information about actual implementability and related concerns for the recommendations. The focus groups are:

- Focus A: Solar thermal fuels, hydrogen roadmaps
- Focus B (1): Hydrothermal carbonation of CO₂
- Focus B (2): Integration of geothermal energy harvesting in temporary CO₂ storage
- Focus C: Building acceptance among landowners/users

Regarding **focus A** a stakeholder analysis was prepared by interrogating the problem and the research [2]. This stakeholder analysis is shown below in Figure 1. Two of these stakeholders were selected, namely Synhelion (in the “Forerunners” group) and Mabanaft (in the “Off-takers” group). In both cases, the recommendation for action from the *Netto-Null-2050 Wegweiser* chosen for consultation with these stakeholders was “11c: Demonstration plant with 10 MW”. This specific item recommended the construction of a demonstration project for the production of solar fuels not later than 2030 by Helmholtz and non-Helmholtz research institutions and industry (as it also required certain access to existing infrastructure).

For **focus B (1)** two stakeholders were selected: Stadtwerke Karlsruhe and the Bavarian Coordination Office for Deep Geothermal Energy of the Technical University of Munich (TUM) reflected the recommendations for action M1a and M1b from the *Netto-Null-2050 Wegweiser*. Both recommendations deal with the development and implementation of geothermal heat storage projects. This recommendation could thus be examined from the perspective of the energy industry as well as research and business development.

Regarding **focus B (2)** two stakeholders were selected: (1) VNG AG (Leipzig, Germany), a large-volume European importer and distributor of natural gas that also provides transport and storage infrastructure and (2) CEMEX AG (Rüdersdorf, Germany), a major producer of cement and other related construction material products. Recommendations O1a (VNG AG; “gas storage in subsurface or technical storages”) and K1 (CEMEX AG; “safe and permanent storage of CO₂”) were chosen from the 'Net-Zeo-2050 Wegweiser' for discussion with the respective representatives of the companies (Mr. Gerd Wölbling from VNG AG and Mr. Philipp Roder from CEMEX AG). Both recommendations were ought to be examined in the light of CCUS, incorporating the view of large industrial CO₂ emitters (CEMEX AG) and providers of large-volume gas storage facilities and transport infrastructure (VNG AG).

For **focus C** two stakeholders were selected: Franziska Tanneberger, director of the Greifswald Moor Centrum, as a key expert and actor with broad expertise of all scientific, technical, and societal aspects of peatland rewetting, and Anje Marten of the Brandenburg State Agency for the Environment (LfU) as someone with frequent and direct interaction with landowners and users. Both discussed recommendation E1 (updating emission factors) and E2 (area management and owner/user interaction), with Anje Marten being more involved in the latter.

In each of the focus groups, one or two interview partners and corresponding recommendations for action were identified. In small interview settings, the recommendations have then been discussed and categorized with one or two of the selected key experts. In addition to the interviewer, a project partner was also present during the interview as the project expert on the respective topic.

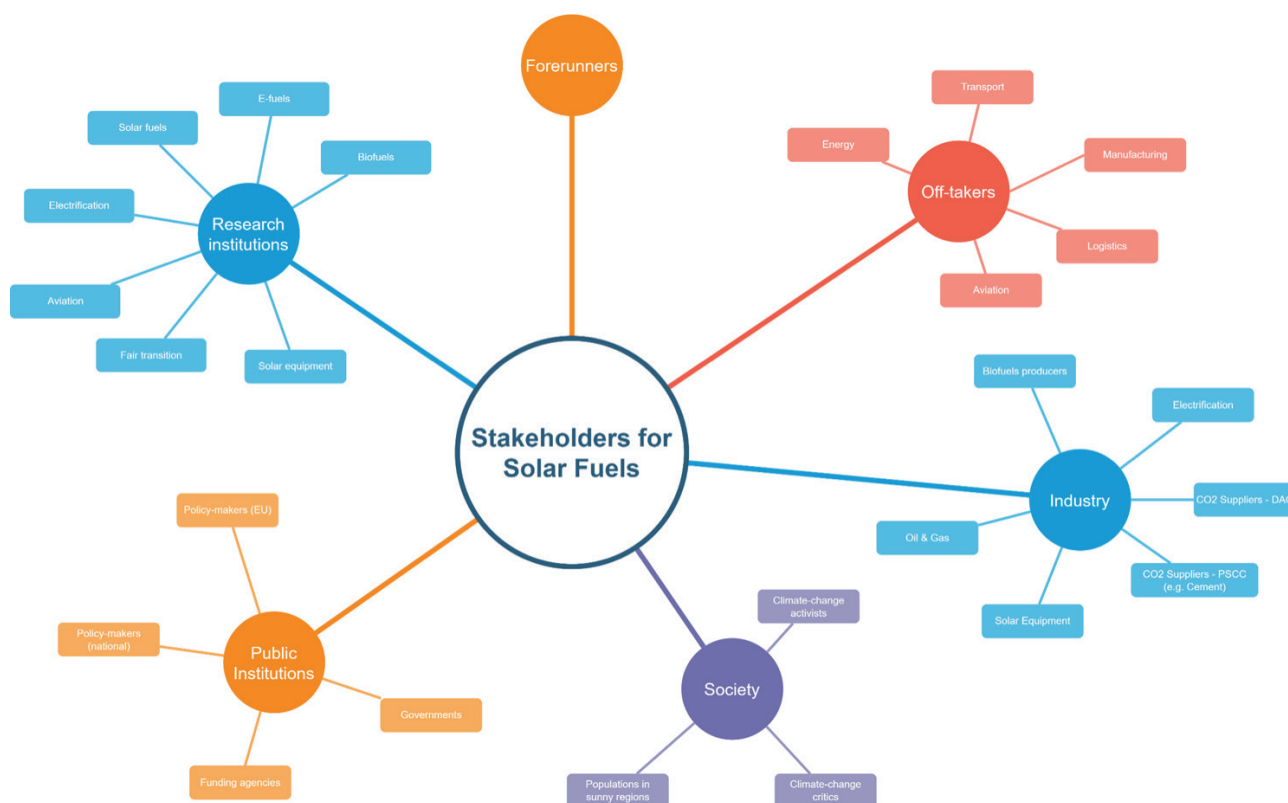


Figure 2: Stakeholder analysis for solar fuels (Focus A: Solar thermal fuels).
Template for documentation of stakeholder interaction

First, the Net-Zero-2050 project, the *Netto-Null-2050 Wegweiser* and the relevant recommendation(s) for action were briefly presented and explained. Afterwards, five open questions were asked in the first part of the interview. The main objective here was to examine the recommendations for action in terms of their relevance and feasibility with the experts from the field or with a practical background. The five questions were introduced with “From your point of view, ...”:

General:

- What do you think of the recommendation for action?

Detailed questions:

- Do you think that the proposed instruments are suitable and target-oriented?
- Do you think that the list of actors (category 'Beteiligte') who need to be involved is complete?
- Do you think that the time frame is realistic?
- Do you think the monitoring method is suitable?

If the recommendation for action was classified as 'not relevant' in question 1, the following alternative questions were asked (instead of questions 2-5):

- Why do you consider the recommendation for action to be 'not relevant'?
- What recommendation for action would you consider appropriate instead?
- Which instruments would be useful for this?
- Which actors ('Beteiligte') should be involved?
- What timeframe do you consider realistic?
- Which monitoring method would be suitable for this?

For the second part of the interview, five closed questions were asked by means of an online tool. Here, the expert could choose a number from one to six to indicate the respective importance, effort, success etc. A 'one' indicated little, low e.g. importance and a 'six' represented a large amount, high e.g. importance. Again, these questions were introduced with “From your point of view...”:

- How important do you consider the collaboration of several actors such as research, industry and society?
- How much effort do you think it will take to implement the measure?
- How certain do you think the success of the measure is?
- What do you think is the measure's contribution to achieving the net zero emissions target?
- How well do you think the success of the measure can be monitored?

W.P 1.2: Performance of stakeholder interactions

Performance and documentation of stakeholder interactions

The nine Net-Zero-2050 stakeholder interviews took place in July and September 2024. Project 1 coordinated, supported and guided the interactions between the consortium's experts and the stakeholders.

Focus A: Solar thermal fuels, hydrogen roadmaps

The interaction with Synhelion (“Forerunners” group) can be summarized with the following bullet points:

- The production of solar fuels is very important because it is not dependent on biomass and is therefore not limited by the same issues as biofuels. However, this is also a disadvantage at the moment, as biomass-based processes are currently more economical and mature. For this reason, they are currently investigating processes based on biogas, but are considering using atmospheric CO₂ as a feedstock in the future.
- The main challenge for the technology is to achieve a high level of efficiency despite the high temperatures over a sustained period. This could be achieved by improving heat recovery, thermal energy storage and collecting data on long-term operation. While a demonstration project can help, the technology is not yet ready for a 10 MW plant in 2030 from their point of view, as mistakes at higher scales are more expensive.
- The cooperation of several actors (e.g. research, industry or society) is very important to realise the potential of the technology, which is seen as a very challenging undertaking. At present, the potential of the technology to address GHG emissions is still in the medium range, but this would change in the near future. However, the technology is competing with other alternative routes to fuel production that may also be successful, so there is a degree of uncertainty. Finally, the potential to measure the performance of the technology is straightforward, as it is easy to compare different pathways for the production of synthetic fuels.

The interaction with Mabanft (“Off-takers” group) can be summarized with the following bullet points:

- The technology is of significant importance to them as the production of carbon monoxide via alternative pathways to reverse water gas shift is a key priority. When compared to other technologies, the 10 MW scale may appear high, however, the scale required to prove the viability of a process can vary significantly between technologies.
- From their perspective, the development of the demonstration project is more favorable if it takes place in Germany or in locations with sufficient engineering, scientific, and funding support. At the demonstration scale, there is no need to produce cheap molecules. However, the timeline is tight (referring to 2030) due to the urgent need for synthetic fuels. By the time the solar fuel technology is fully developed, another suboptimal technology could already dominate the market.
- The cooperation of different societal actors is considered very important for this technology, especially from a regulatory perspective. According to the interview, the effort required to develop the technology is also expected to be high, and given the very competitive field with other technologies in terms of cost, the potential success is rated as rather low, although the potential impact it could have towards a net-zero future is very high.

Focus B (1): Hydrothermal carbonation of CO₂

Focus Area B (1) dealt with stakeholder interaction on the topic of geothermal heat storage for urban areas, which could also serve as a basis for new CO₂ storage concepts. Two interactions were carried out in the Upper Rhine region and evaluated as a basis for further development. This region has great geothermal potential, which also applies to deep underground storage with regard to former oil reservoirs. One particular focus was on the DeepStor research infrastructure for heat storage in Karlsruhe at KIT Campus North.

The first interaction in the context of two events was a cooperation with the Mobile Participation Lab “MobiLab” of the KIT Center Humans and Technology. The focus was on two stakeholder groups: citizens in the first dialog event and political decision-makers and members of the administration, including delegates of the Upper Rhine Conference (see Figure 2), in the second. The events were also intended to provide information on whether and with which offers the MobiLab can be used for interaction with the population on the use of geothermal energy. An exhibition with various levels of participation ranging from information (posters, tablets with maps) and hands-on offers such as an experiment kit and a seismometer to elements for participation (“installation for networked thinking”) were offered. We conducted quantitative interviews with the visiting citizens on their assessment of the use of geothermal energy (see Figure 3) and qualitative interviews with political and administrative representatives. The small number of cases of around 20 interviews does not allow any general conclusions to be drawn, but does allow trends to be identified.



Figure 3: The MobiLab at the Kronenplatz in Karlsruhe. We invited citizens to learn about geothermal technologies and get in dialogue with researchers (photo: Bremer, KIT).

The qualitative assessment led to a further development of the individual formats. Discussions with decision-makers revealed that they see a need for knowledge-based information on the topic of geothermal energy for the general public. The MobiLab proves to be a suitable contact point for interactions over a longer period of time (several days to weeks). Due to the space available, workshops or courses can be integrated and offered on its platform. Short-term assignments require more flexible concepts and are more difficult to manage with the MobiLab due to the effort involved.

The further development initiated by these events led to an exhibition in an established dialog space in the city center of Karlsruhe (Triangel). In the second interaction with the population and stakeholders on the topic of geothermal heat storage, the following exhibits were prepared:

1. Virtual reality representation of the subsurface (composition, geology, utilization for heat storage) as an elevator ride into the depths with VR glasses
2. Interactive 3D representation of the heat storage cycle in DeepStor on a screen
3. Plug-and-play seismometer to measure induced seismicity for playful experiments and to teach risk management strategies
4. Experiment kit for playful communication of rock properties
5. Poster to impart knowledge about geothermal technologies and geothermal projects in Germany
6. Presentation on the topic

The exhibition was supervised by the scientists and a social science team evaluated the exhibition using questionnaires and interviews. A one-off presentation was held in the exhibition rooms to provide more in-depth information on the concepts of storage and its significance in the energy system. The most important results can be summarized as follows:

- Overall, the exhibition stations were well suited to imparting knowledge on the topic of deep geothermal heat storage, which was documented in the subjective assessment of the increase in knowledge.
- The VR glasses played a special role in the exhibition. On the one hand, they were an important factor in arousing interest in the personal approach. On the other hand, they presented several challenges in terms of human-technology interaction. For this exhibit in particular, the technology of the format could be better exploited through greater interactivity.
- The majority of visitors showed an interest in actively participating in research (here, the Citizen Science format with easy-to-use seismometers, “Raspberry Shakes”).

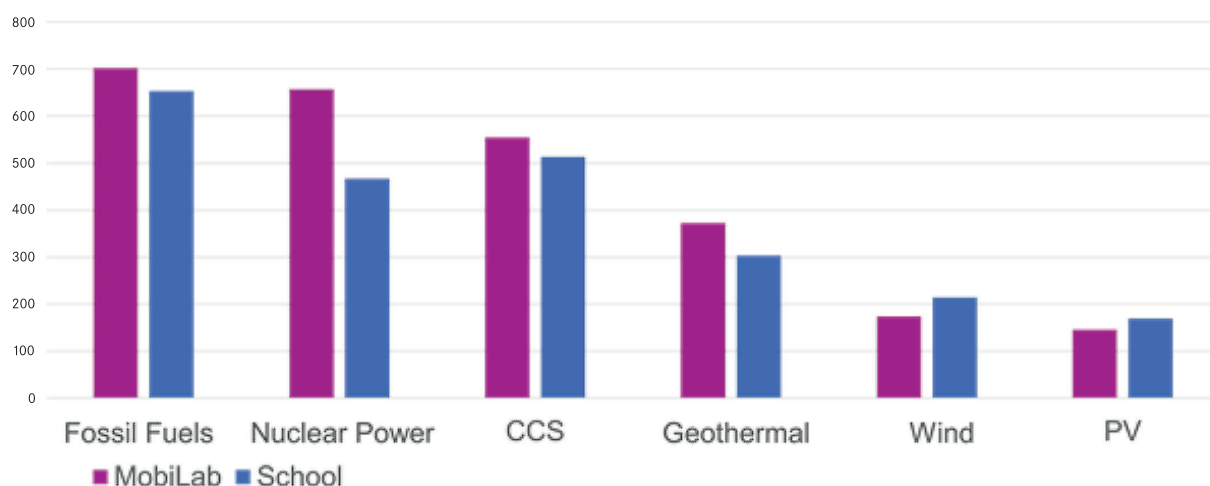


Figure 4: Comparative risk evaluation of several energy technologies (on a scale between 0 and 1000) by citizens visiting the first MobiLab event in comparison to a group of pupils. CO₂ storage technologies are precepted as quite risky, but not as risky as fossil fuels and nuclear power (photo: Bremer, KIT).

Focus B (2): Integration of geothermal energy harvesting in temporary CO₂ storage

The stakeholder interaction resulted in the following points:

- strong incentive for emitting industries to deploy CCUS technologies incorporating safe and permanent storage of CO₂ from a technological point of view, but the capital and operational costs of these measures threaten the profitability of the product lines and the companies as a whole,
- risk of shifting product lines outside of the country for the sake of profitability and compliance with the carbon budget,
- lack of realistic time frames and legal frameworks for CO₂ storage in Germany,
- some form of CO₂ storage within the German land and maritime borders will be necessary.

Focus C: Building acceptance among landowners/users

The stakeholder interaction led to the following main points:

- Land and Water Management: Rewetting requires addressing both land and water rights, securing owner consent, and engaging stakeholders.
- Financial and Legal Incentives: Offer financial compensation and legal clarity to encourage participation. Strengthen moor protection and water retention in federal laws.
- Funding and Implementation: Ensure sufficient funding for rewetting and support project leaders and existing organizations.
- Public Engagement: Invest in public communication and community engagement.
- Agricultural Policy: Amend the Common Agricultural Policy (CAP) to support wet farming and consider temporary grassland conversion for establishing vegetation.
- Prioritization and Compensation: Establish priority areas for moor protection, compensate farmers for reduced yields.
- Private Sector Involvement: Involve private investors for biomass utilization, offering economic incentives like CO₂ reduction or certificates.
- Streamlining Regulations: Simplify water laws to facilitate moor protection projects.
- Monitoring and Integration: Prioritize implementation over extensive monitoring and integrate landowners through incentives or legal changes.
- Water Retention: Recognize the importance of water retention for cooling and quality of life.

Additional key points were:

- Greenhouse Gas Reporting: Improve Germany's greenhouse gas reporting and use biogeographically regional emission factors.
- Holistic Approach: Moor rewetting has co-benefits that should be considered.
- Capacity Building: Build capacity for rewetting moors with specialists in planning and water engineering.
- Acknowledge Experiences: Build on the experiences of the countries, not from new.
- Land Verification: Ensure land reported as rewetted is actually wet.

W.P 1.3: Synthesis & dissemination

The analysis aimed to develop and assess the feasibility of several climate change mitigation measures derived from the *Netto-Null-2050 Wegweiser*, focusing on the practical implementation of these strategies. The work utilized a structured methodology consisting of three key steps: expert interviews, exploratory multicriteria decision analysis (MCDA), and an additional assessment of relevant goals and measures for the energy transition based on a literature review.

The reality check was organized around a three-step framework:

1. Expert Interviews (Method Step 1)

After selecting action recommendations and forming thematic focus groups, relevant practitioners were identified and invited for interviews. Each interview discussed one action recommendation in-depth, providing insights into its perceived feasibility and potential barriers to implementation. These insights were categorized and linked directly to the specific recommendations.

2. Multicriteria Decision Analysis for Implementation (Method Step 2)

The MCDA was used to evaluate the implementation feasibility of selected recommendations based on five key characteristics: collaboration importance, implementation effort, contribution to goal achievement, implementation success likelihood, and assessment of a functioning monitoring process. Given the uncertainty surrounding the relative weightings of these criteria, a geometric, computer-based method was used to evaluate the robustness of decisions under varying preference scenarios. This approach visually captured the sensitivity of decision outcomes to changes in stakeholder preferences. Multiple scenarios were assessed, ranging from uniform weighting to scenarios where one criterion was prioritized over others. These scenarios helped determine how changes in preferences might affect the perceived feasibility of each action.

3. Literature Review (Method Step 3)

In addition to expert interviews, a reality check was conducted using published statements and reports on energy transition goals and pathways. This included evaluations from the Helmholtz Climate Initiative's *Netto-Null-2050 Wegweiser* and associated studies. These analyses served as an independent confirmation of the practicality of selected measures, thereby supporting the overall assessment of the *Wegweiser's* viability.

The analysis provided several key findings:

1. Feasibility of Action Recommendations

The implementation feasibility of selected recommendations was evaluated under different weight scenarios, revealing that specific measures, such as the Transport Network Analysis for all gases, were considered more feasible when all criteria were weighted equally. Other measures, like the Quantification of Greenhouse Gas Dynamics in Re-wetted Peatlands, showed stronger feasibility when factors such as implementation effort were prioritized. Secondary results emerged from the analysis of the robustness of the implementation process. For example, the CCS Guidelines required substantial collaboration between stakeholders and society to become feasible. If such collaboration is achieved, the feasibility of this action could significantly increase. The Hydrogen Analysis for Storage and Quantity and Geo-Thermal Storage Development were also identified as more challenging, requiring further research and stakeholder engagement.

2. Sensitivity of Decision-Making to Criteria Weights

The sensitivity analysis showed that while the ranking of recommendations remained relatively stable across different scenarios, slight shifts in stakeholder preferences (such as a stronger emphasis on implementation effort) could lead to a reordering of the most feasible measures. This highlights the importance of considering how decision-maker priorities might evolve and the robustness of proposed measures but stresses the importance of taking action.

3. Assessment of the Net-Zero-2050 Pathways

For the recommendations for action on the energy system, the DLR first updated the texts and legal basis before publishing the *Netto-Null-2050 Wegweiser*, based on the new regulations that have since been introduced by the government, the so-called “Ampelregierung”. In addition to the interviews conducted as described above, a reality check was carried out for selected relevant targets, measures and development paths for the energy transition based on published statements and expert studies. These were derived from the recommendations for action developed as part of the Helmholtz Climate Initiative from the *Netto-Null-2050 Wegweiser* guide and the underlying Net-Zero-2050 scenario (Simon et al. 2022) and relate to the topics of energy efficiency targets, expansion of renewable electricity generators and heat pumps, ramp-up of electromobility, decarbonisation of industry and expansion of the electricity transmission grid. Expertise from current studies, comments from interest groups and statements in the media were evaluated and each was compiled into a short report of no more than two pages. As a result, it is possible to assess whether the targets and path developments from the Net-Zero-2050 scenario and other target-oriented scenario studies appear achievable in the various areas and which further measures are proposed from different perspectives to accelerate the transformation processes compared to the current boundary conditions.

Reality-Check Report

The resulting report is the central, overarching deliverable of the second funding phase. It presents the detailed results of this work, summarizing feedback from stakeholders outside the immediate scientific community as well as from expertise outside the Net-Zero-2050 consortium and analyzing its impact on the formulation of the original recommendations. The analysis represents a valuable contribution to the field of climate policy analysis by providing a systematic framework for evaluating the practical implementation of climate change mitigation strategies. Integrating expert opinions with explorative decision analysis techniques allows for a deeper understanding of the factors influencing the success of these strategies. The project also highlights the need for ongoing adjustments and responsiveness to shifting stakeholder preferences as the transition to net-zero emissions progress. Future research should focus on refining the decision-making models and expanding the scope of the analysis to include additional action recommendations.

The report “**Netto-Null-2050 Reality-Check – von praxisorientierten Handlungsempfehlungen und Strategien für ein CO₂-neutrales Deutschland bis 2050**” is published on the funding measure’s websites (www.netto-null.org | www.helmholtz-klima.de).

Net-Zero-2050 Summer School

An additional activity, namely the one-week summer school in September 2024, made a major contribution to the dissemination and communication of the Net-Zero-2050 idea. It took place in the Chilehaus, the location of the Climate Service Center Germany (GERICS/Hereon). It was attended by 14 doctoral students and postdocs who partly had a background with net-zero related topics. They were given insights into various strategies and possible measures that are being researched within Net-Zero-2050. The presentations covered, for example, a

systemic overview of how the achievement of net-zero CO₂ emissions can be approached (see Figure 4, left), technologies for hydrogen production and storage, membrane processes for capturing CO₂ as well as carbon cycles and renewable energies. Participants were also able to present their own research work in short pitches.

The summer school program also included excursions that offered a practical insight into the research and implementation of CO₂ reduction or CO₂ avoidance options. The excursions included the Algae House in Hamburg Wilhelmsburg (see Figure 4, right), the Helmholtz-Zentrum Hereon to visit various research laboratories and the Baltic Sea peninsula of Priwall in Lübeck to learn about the coastal ecosystem and how it can be adapted to the consequences of climate change. During the summer school days, the participants could expand their professional expertises and their networks.

The organization of the summer school was the responsibility of GERICS/Hereon, but numerous colleagues from a total of four Helmholtz centers actively participated in the program – in the form of lectures, excursions or in-depth technical discussions: Torsten Brinkmann (Hereon), Daniela Jacob (GERICS/Hereon), Thomas Klassen (Hereon), Fiona Köhnke (GERICS/Hereon), Enric Prats Salvadó (DLR), Thomas Pregger (DLR), Björn Rau (HZB), Imke Rhoden (FZJ) and Bettina Steuri (GERICS/Hereon).

The summer school was a complete success, as shown by the answers in a *short film* with the participants. A second round is already being planned, this time as a winter school in November 2025.



Figure 5: Prof. Daniela Jacob, director of the Climate Service Center Germany (GERICS), is giving an introductory talk about the net-zero topic (left; photo: Hereon/Bettina Steuri). The participants of the summer school in front of the Algae House in Hamburg Wilhelmsburg (right; photo: Hereon/ Cecilia Steffi Lukman).

REFERENCES

[1] Jacob, D., El Zohbi, J., Köhnke, F., Abetz, V., Baetcke, L., Ball, C., Bauer, F., Beck, S., Berkel, M., Blome, T., Borchers, M., Brinkmann, T., Bruhn, D., Chi, Y., Dahmen, N., Dittmeyer, R., Dolch, T., Dold, C., Dornheim, M., Fogel, S., Förster, J., Fuchs, S., Gardian, H., Gawel, E., Görl, K., Groth, M., Hamedimastana-bad, H., Hampel, U., Harpprecht, C., Herbst, M., Heß, D., Kalhori, A., Kiendler-Scharr, A., Klassen, T., Koop-Jakobsen, K., Korte, K., Kuckshinrichs, W., Li, Z., Markus, T., Mayer, M., Mengis, N., Monnerie, N., O Corcora, T., Oschlies, A., Pardo Perez, L.C., Prats Salvado, E., Pregger, T., Preuschmann, S., Rau, B., Rechid, D., Reusch, T., Rho-den, I., Riehm, J., Roeb, M., Rolletter, M., Sachs, T., Sattler, C., Sauer, J., Schaller, R., Schätzler, K., Schill, E., Schmidt-Hattenberger, C., Schultz, M., Simon, S., Steiner, U., Steuri, B., Stevenson, A., Sun, J., Thoni, T., Thrän, D., Unger, S., Vögele, S., Waczowicz, S., Weihermüller, L., Xiao, M., Yeates, C., Zwickel, P.: *Netto-Null-2050 Wegweiser* - Strategische Handlungsempfehlungen und mögliche Wege für ein CO₂-neutrales Deutschland bis 2050, Version 1.0, 2023.

[2] Bammer, G. (2021, October 21). Stakeholder engagement primer: 2. Identifying stakeholders. i2INSIGHTS.
<https://i2insights.org/2021/10/21/identifying-stakeholders/>

ADDITIONAL ACTIVITIES

Hereon/Membrane

One main research focus of the Institute of Membrane Research of Hereon is the development of membranes and membrane technologies for CO₂ related applications. This includes the separation from various gas streams, the supply of hydrogen for utilization purposes as well as membrane supported CO₂ utilization routes. Examples for activities are the investigation of CO₂ separation from the flue gas of a gas power plant installed in the AG der Dillinger Hüttenwerke steel mill where CO₂ could be purified to > 98 mol-%. For a joint project with the cement producer Holcim and the Hereon licensee Cool Planet Technologies large scale membrane modules were designed, built and equipped with membranes resulting in membrane modules that are amongst the largest ones ever produced for gas separation applications. Both projects are funded by the German Federal Ministry of Economic Affairs and Climate Action.

The related work progress of Hereon's Institute of Membrane Research follows from the described results: membranes and membrane modules were produced. They were tested in pilot plants. The experimental results could be well described by Hereon developed simulation tools.

HZB

To reach a successful transformation towards a climate resilient society, the interaction of science towards the relevant stakeholders and vice versa is key. Scientific knowledge as well as technological approaches must be transferred into the community. But at the same time, the needs, sensitivities and realistic opportunities of the individual target groups must be considered to generate the highest impact with respect to the mitigation of the effect of climate change and the optimum adaptation of the unavoidable consequences of climate change. In this sense, HZB contributed also to different activities of stakeholder communication within phase 2 of the project. An expert from the HZB Consulting Office for Building-integrated Photovoltaics (BAIP), the institution for knowledge transfer and stakeholder exchange with the community of architects, planners and building owners, actively contributed to the organization and implementation of the Net-Zero-2050 Summer School in September 2024. During the GERICS conference "Climate services for climate-resilient cities and regions" in November 2024 a representative of BAIP introduced the advantages and opportunities of building-integrated photovoltaics to the participating experts from urban planning, local politics and other fields of sustainability.

HZB took part in the regular project meetings, discussed the progress of the project and contributed actively to the transdisciplinary exchange between the project partners from the different centers and research fields. HZB also participated both in the organization committee and with 3 participants in the Net-Zero-2050 summer school.

SPECIAL FEATURES

Hereon/GERICS and all project partners

During the second project phase, the **Net-Zero Network** was launched. While the project consortium constituted the initial members, the network was then opened to all interested parties from science and practice. The goal is to promote scientific exchange on negative emissions, CO₂-neutrality as well as climate resilience by organising different events such as lectures, workshops and conferences.

DLR

The interaction with stakeholders has proven to be valuable for two reasons: on the one hand, it allows the validation of the recommendations for action from the *Net-Zero-2050* Guide and, on the other hand, fosters the dialogue between different actors.

Hereon/Membrane

Membrane based CO₂ separation was presented in the scope of the summer school 02. to 06. September 2024. A membrane unit in action was demonstrated to the participants at an innovative building in Hamburg where membrane technology is used to supply CO₂ to algae bio reactors serving as facade elements.

OUTLOOK ON FUTURE WORK

Hereon/GERICS together with all centers

After the successful Net-Zero-2050 Summer School 2024, the **Net-Zero Network** will continue to organize yearly summer or winter schools. The focus will still be set on transdisciplinary research on a carbon-neutral society with changing excursions. Additionally, early-career scientists also from other research associations and universities will be invited in the future.

Hereon/GERICS

The Net-Zero-2050 consortium will continue with their cooperation as the **Net-Zero Network**, which was established during the second phase of Net-Zero-2050. The **Net-Zero Network** promotes scientific exchange on negative emissions and CO₂-neutrality. Interested parties from science and practice are invited. The aim is to further expand the network and, in addition to the organization of future summer and winter schools, the **Net-Zero Network** will organize different events to foster exchange and joint work and research on net-zero and climate related topics.

Hereon/Membrane

The described work on membrane-based technologies for achieving a net-zero society will be continued. One big element will be the installation of a membrane demonstration plant for CO₂ separation at a cement plant, where Holcim, Cool Planet Technologies and Hereon's Institute of Membrane Research collaborate. A similar plant will be designed for the treatment of the flue gas of Hereon's own combined heat and power plant. Other CO₂ points sources will be addressed as well. Furthermore, membrane development will be continued aiming at higher permeances as well as an increase of CO₂-selectivity for certain applications as those with low CO₂ concentrations in the off-gas. The results will be presented in the next summer school.

DLR

The involved institutes support the organization and implementation of the future summer and winter schools and strive for further networking with the Helmholtz climate researchers. The topic of integration and evaluation of different mitigation measures in climate protection and in particular the interplay between mitigation options through substitution of fossil fuels and negative emissions through CO₂ sinks has great potential and helps to characterize realistic and feasible development paths. Collaboration is conceivable through cross-program cooperation within the Energy and Earth & Environment research programs and can also be strengthened through joint third-party funding acquisitions and publication projects.

FZJ

The organization and implementation of the future summer and winter schools will be supported. Furthermore, FZJ strives for further collaboration with the **Net-Zero Network**. The research on approaches to account for the different perspectives of stakeholders will be continued. Assessments of net-zero solutions, especially under a regionalized perspective, are planned to be another focus.

KIT

The dialog events have shown that there is a great need: There is little knowledge about geothermal technologies. At the same time, the topic is associated with emotions, especially fears. There is a need for opportunities for participation in both research and operational projects. We will therefore continue to focus intensively on communicating the potential uses of deep geothermal energy and storage in particular. The pilot dialog formats within WP1.2 Focus B (1) specifically help to evaluate and further develop interaction formats. In this way, stakeholder interactions are further developed in a stakeholder-specific manner. The results will also flow into science communication on the DeepStor and GeoLaB research infrastructures.

PUBLICATIONS

- **Netto-Null-2050 “Reality-Check” – von praxisorientierten Handlungsempfehlungen und Strategien für ein CO₂-neutrales Deutschland bis 2050.**
Jacob, D., El Zohbi, J., Köhnke, F., Brinkmann, T., Dittmeyer, R., Fogel, S., Hampel, U., Klassen, T., Markus, T., Mayer, M., Monnerie, N., Prats Salvado, E., Pregger, T., Kronshage, S., König, R., Rau, B., Rhoden, I., Sachs, T., Schätzler, K., Schill, E., Steuri, B. (2025).
- **A storyline approach: integrating comprehensive, interdisciplinary research results to create narratives in the context of the net-zero target in Germany.**
Köhnke, F., Steuri, B., Baetcke, L., Borchers, M., Brinkmann, T., Dittmeyer, R., ... & Jacob, D. (2024). Frontiers in Environmental Science, 12, 1433491.
- **Membranbasierte Bereitstellung von CO₂ für die dezentrale Algenproduktion in einer Bioenergiefassade**
Wolff, T., Brinkmann, T., Scholles, C. & Kerner, M. (2023). Chemie Ingenieur Technik, 95, No. 12, 2015–2021, DOI: 10.1002/cite.202300099.

EVENTS

— 1. Stakeholder Interaction - Citizens, focus area B (1)

Topic Geothermal Energy @ Mobile Participation Lab "MobiLab" in Karlsruhe

Organizers: Katharina Schätzler, Judith Bremer, Jerome Azzola (KIT)

together with Richard Beecroft & David Huber (KIT), KIT-Center Humans and Technology

Date: 10-13 October 2023

Format: on site

Participants: Citizens

— 2. Stakeholder Interaction - Decision makers, focus area B (1)

Topic Geothermal Energy @ Mobile Participation Lab "MobiLab" in Rastatt

Organizers: Katharina Schätzler, Judith Bremer, Jerome Azzola (KIT)

together with Richard Beecroft & David Huber (KIT), KIT-Center Humans and Technology

Date: 25 April 2024

Format: on site

Participants: Delegates of the Upper Rhine Conference

— 3. Expert interview for the reality check for focus area B (1)

Organizer and interviewer: Fiona Köhnke (GERICS/Hereon)

Net-Zero-2050 expert: Stefan Fogel (HZDR)

Date: 01 July 2024

Format: online

Participant: one practitioner selected by the Net-Zero-2050 expert

— 4. Expert interview for the reality check for focus area B (1)

Organizer and interviewer: Fiona Köhnke (GERICS/Hereon)

Net-Zero-2050 expert: Stefan Fogel (HZDR)

Date: 02 July 2024

Format: online

Participant: one practitioner selected by the Net-Zero-2050 expert

— 5. Expert interview for the reality check for focus area B (2)

Organizer and interviewer: Fiona Köhnke (GERICS/Hereon)

Net-Zero-2050 expert: Katharina Schätzler (KIT)

Date: 05 July 2024

Format: online

Participant: one practitioner selected by the Net-Zero-2050 expert

— 6. Expert interview for the reality check for focus area A

Organizer and interviewer: Fiona Köhnke (GERICS/Hereon)

Net-Zero-2050 expert: Enric Prats Salvado (DLR)

Date: 08 July 2024

Format: online

Participant: one practitioner selected by the Net-Zero-2050 expert

- **7. Expert interview for the reality check for focus area A**
 Organizer and interviewer: Fiona Köhnke (GERICS/Hereon)
 Net-Zero-2050 expert: Enric Prats Salvado (DLR)
 Date: 10 July 2024
 Format: online
 Participants: two practitioners selected by the Net-Zero-2050 expert

- **8. Expert interview for the reality check for focus area A**
 Organizer and interviewer: Fiona Köhnke (GERICS/Hereon)
 Net-Zero-2050 expert: Thomas Klassen (Hereon)
 Date: 17 July 2024
 Format: online
 Participant: one practitioner selected by the Net-Zero-2050 expert

- **9. Expert interview for the reality check for focus area C**
 Organizer and interviewer: Fiona Köhnke (GERICS/Hereon)
 Net-Zero-2050 expert: Torsten Sachs (GFZ)
 Date: 26 July 2024
 Format: online
 Participant: one practitioner selected by the Net-Zero-2050 expert

- **10. Expert interview for the reality check for focus area C**
 Organizer and interviewer: Fiona Köhnke (GERICS/Hereon)
 Net-Zero-2050 expert: Torsten Sachs (GFZ)
 Date: 11 September 2024
 Format: online
 Participant: one practitioner selected by the Net-Zero-2050 expert

- **11. Expert interview for the reality check for focus area B (2)**
 Organizer and interviewer: Fiona Köhnke (GERICS/Hereon)
 Net-Zero-2050 expert: Katharina Schätzler (KIT)
 Date: 27 September 2024
 Format: online
 Participant: one practitioner selected by the Net-Zero-2050 expert

- **12. Interaction with Citizens Karlsruhe, focus area B (1)**
 interactive exposition about Geothermal Energy Storages Karlsruhe @ Triangel Karlsruhe
 Organizers: Katharina Schätzler, Judith Bremer, Florian Bauer, Jerome Azzola (KIT)
 together with Polina Häfner, Victor Häfner, Felix Michels (KIT INE)
 Date: 21-23 January 2025
 Format: on site
 Participants: Citizens

CLUSTER I: NET-ZERO-2050

Project 2

Technological Options for Carbon Capture
Utilization and Storage

AUTHORS

**Helmholtz-Zentrum
Dresden-Rossendorf (HZDR)**
Stefan Fogel

**Helmholtz-Zentrum
Berlin (HZB)**
Matthew Mayer
Flora Haun

**Helmholtz-Zentrum
Hereon**
Claudio Pistidda

**Karlsruhe Institute of
Technology (KIT)**
Peter Holtappels
Roland Dittmeyer

Centers involved:

SUMMARY

Work Package 2.1: Electrocatalytic CO₂ conversion

A carbon-neutral chemical industry requires the use of sustainable chemical feedstocks and be powered by renewable energy. The electrocatalytic conversion of carbon dioxide to valuable chemicals, driven by electricity, is a promising approach toward achieving circular carbon utilization. Electrolysis of CO₂ can produce a range of different commodity chemicals, but usually as an uncontrolled mixture including undesired side products, and therefore controlling reaction selectivity is a central obstacle to advancing the technology. Efforts are needed in the design of advanced catalyst materials, the development of scalable reactor concepts, and obtaining a detailed understanding of dynamic processes in the reactor which influence selectivity. We made progress on each of these points in the project, including examining novel intermetallic catalysts, developing gas diffusion reactors operating at high temperature and pressure, and developing in-situ methods (spectroscopy, diffraction, and imaging) to observe key processes during reactor operation.

Work Package 2.2: Demonstrator concept for CO₂ cycle with temporary subsurface storage

Large-scale approaches for the circular use of carbon dioxide entangled with suitable high-capacity storage options comprise important technological options for a Net-Zero economy. Based on the outcome of the first phase of the HI-CAM project, further studies were conducted with regards technological options and potentials of combined temporary subsurface storage of CO₂ (e.g. from industrial plants from hard-to-abate industries) in combination with geothermal heat harvesting. Temporarily stored CO₂ can be back-produced from the subsurface storage at high pressures. Subsequently, the retrieved CO₂ can be converted to methane (CH₄) together with hydrogen (H₂) from intermittent renewable sources, such as wind and PV. The produced synthetic natural gas (SNG) or CH₄ can be stored within a suitable subsurface store and reused during times of high demand of electricity and insufficient renewable production. SNG is subsequently combusted within a supercritical power cycle utilizing CO₂ as working fluid. This process provides, besides electrical energy and heat, clean and pure CO₂ which is collected and stored again in the subsurface store for geothermal heat recovery as well as a fully circular use of carbon dioxide.

The power-production cycle of the storage plant concept based on supercritical CO₂ as working fluid is still in its early stages of development and systemic theoretical and experimental assessments are scarce. This sub-project therefore studied the application of novel SNG-fired Allam reversion cycles, which allow for a confined and circular use of CO₂/CH₄ and thus an emission-free storage of intermittent renewable electricity. System modeling and simulation studies of the storage cycles were conducted as a proof-of-principle at relevant system scales. Within these analytical procedures, the principal surface components were defined by means of flow charts, appropriate subsurface storage sites and CO₂ emitter clusters for the storage/plume establishment were studied and the respective data was collected. The outcome of this sub-project within Net-Zero-2050 Phase 2 will be used to derive a conceptual engineering design specifying the circuit and its components as well as control structures as a link to the experimental facility CARBOSOLA at HZDR. The work serves as a base point for future research projects and technology transfer towards industrial deployment.

ACHIEVED RESULTS

Work Package 2.1: Electrocatalytic CO₂ conversion

High-pressure high-temperature electrochemical cell operational at TRL2

The electrochemical reduction of CO₂ suffers from relatively low current densities and high overpotentials. Reaction rates can be accelerated by increasing the temperature, while elevated pressure may favor the production of multi-carbon products. In a parallel project to HI-CAM Phase 2 a test rig has been established at KIT-IMVT, that allows the testing of zero gap cells at temperatures up to 200 °C and pressures up to 20 bar. Figure 1 shows the zero gap electrolyzer cell and the test rig.

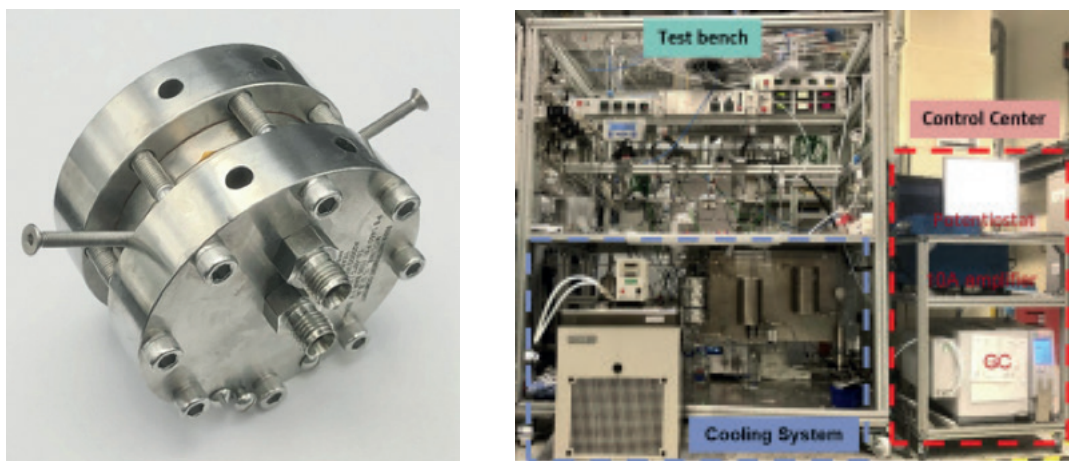


Figure 1: Zero gap electrolyzer cell for testing at elevated temperature and pressure (left); full test rig for the CO₂RR experiments (right).

Using PBI based HT proton exchange membranes, full cell tests using Ti based anode and Ag as well as Cu based cathodes have been performed up to 180 °C. For Cu electrodes, the selectivity to C₂⁺ compounds decreases with increasing temperature resulting in hydrogen formation with faradaic efficiencies exceeding 80%. For Ag cathodes the high selectivity towards the formation of CO at low temperatures also decreased with increasing temperature favouring the hydrogen production with a faradaic efficiency (FE) of 70% at 180 °C and a current density of 200 mA/cm² (@ cell voltage 3.3 V). Interestingly the ratio of CO/H₂ produced is not significantly affected by the current density (see Figure 2). This result is promising as a load independent H₂/CO ratio of 2-3 is advantageous for further downstream synthesis processes such as the Fischer-Tropsch and methanol synthesis.

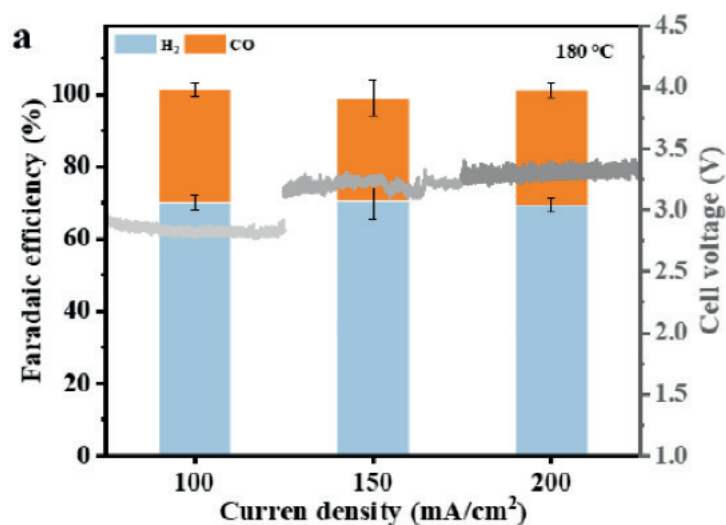


Figure 2: Electrolyzer voltage and product faradaic efficiency of CO₂RR reduction to CO based on silver catalyst at 180°C.

The effect of pressure was investigated on Cu based electrodes for the CO₂ reduction on an anion conducting membrane and at a temperature of 25 °C. The results shown in Figure 3 show the product distribution at various current densities. While at relatively low current densities of 100 mA CO and also ethylene are formed, at higher current densities of 300 mA/cm² the hydrogen production dominates clearly. The product distribution is not significantly by the applied pressure, however, increasing the pressure reduces the cell voltage especially at high current densities.

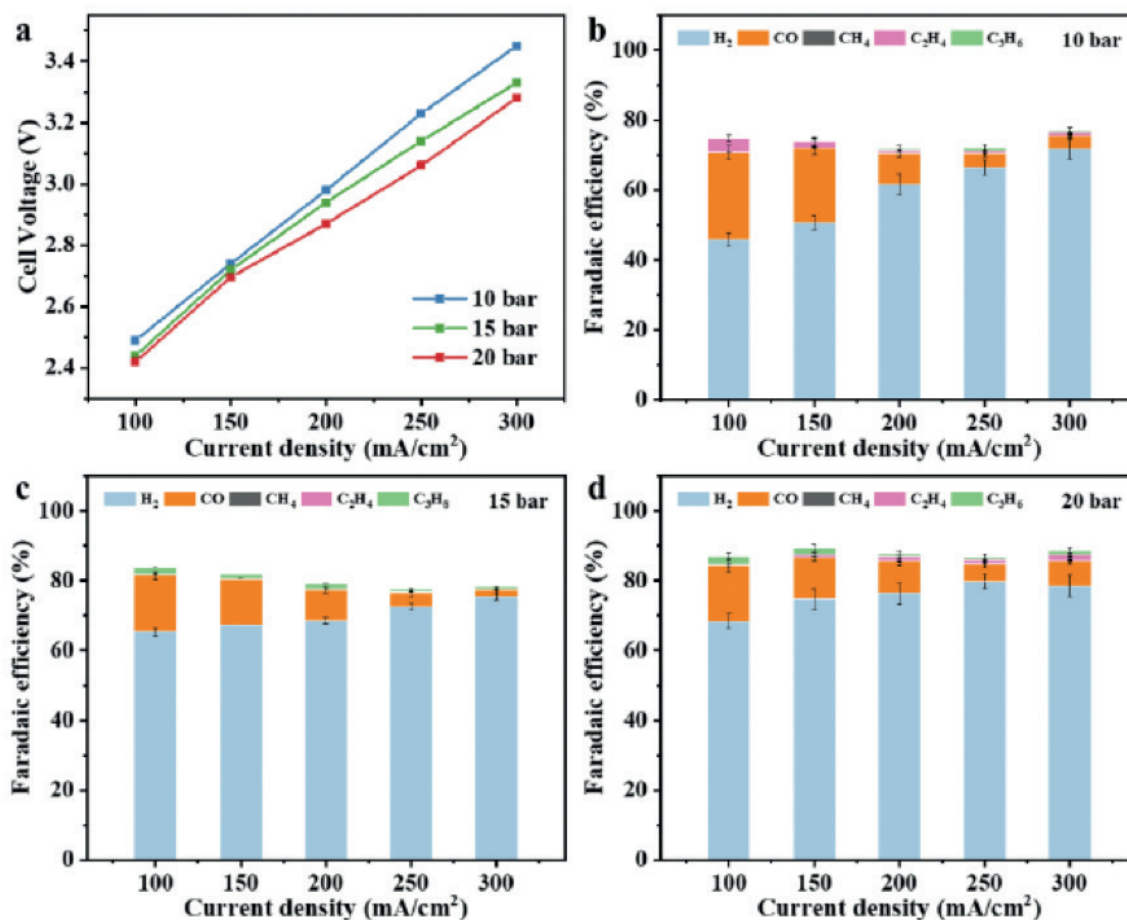


Figure 3: Electrochemical performance under high pressure conditions in 1 M KOH anolyte. (a) Polarization curves. Faradaic efficiencies of the products at a re-action pressure of (b) 10 bar, (c) 15 bar, and (d) 20 bar.

C₂₊ productivity, selectivity and faradaic efficiency at TRL2

Synthesis, efficiency and selectivity of Fe-based hydride catalysts

Achieving higher value multi-carbon (C₂₊) products rather than C₁ products (CO, HCOO⁻, CH₄) requires tailoring the catalytic microenvironment to facilitate C-C bond formation. We addressed this challenge by testing novel catalysts based on mixed metals and copper compounds.

Metal hydride catalysts (previously studied by Hereon for hydrogen storage and thermal-catalytic CO₂ hydrogenation) were considered as possible electrocatalyst, which we hypothesized might help facilitate C-H bond formation during CO₂ reduction. First, we examined Fe₂Ni and Mg₂Ni alloys, which had previously been demonstrated as hydrogenation catalysts, under CO₂ electrolysis conditions in aqueous KHCO₃ solution. Unfortunately, under all conditions tested we observed negligible CO₂ conversion products, while the undesired side reaction of H₂ evolution dominated (data not shown).

Since copper is the best elemental catalyst for C₂₊ production, we decided to replace Ni with Cu and examine the alloy Mg₂Cu, with the hypothesis that the Cu activity could be modulated by incorporation into the alloy. While this catalyst also produced significant H₂, we also observed some CO₂ reduction products, namely carbon monoxide (CO), methane (CH₄), ethylene (C₂H₄), and formate (HCOO⁻). The faradaic efficiency (FE; essentially the electron-to-product efficiency) for all products, when tested at various cathodic potentials, is shown

in Figure 4 (left). While the catalyst produced large yields of the undesired side-product of H_2 , when looking closer at just the CO_2 reduction products (see Figure 4, right) we can observe a strong potential dependence to the product selectivity: at low overpotentials (less negative) the simplest product CO is favored (requiring 2 e^- transfers per molecule), while higher overpotentials resulted in increased C-H bond formation and notably increased C_2H_4 evolution (requiring 12 e^- and 2 CO_2 molecules). The selectivity is comparable to that of pure copper, although Mg_2Cu seems to be favoring hydrocarbon products over oxygenates like alcohols (which were not detected). This is a promising observation, and the Mg_2Cu catalyst will be further studied for optimizing the yield of CO_2 reduction products and suppressing H_2 .

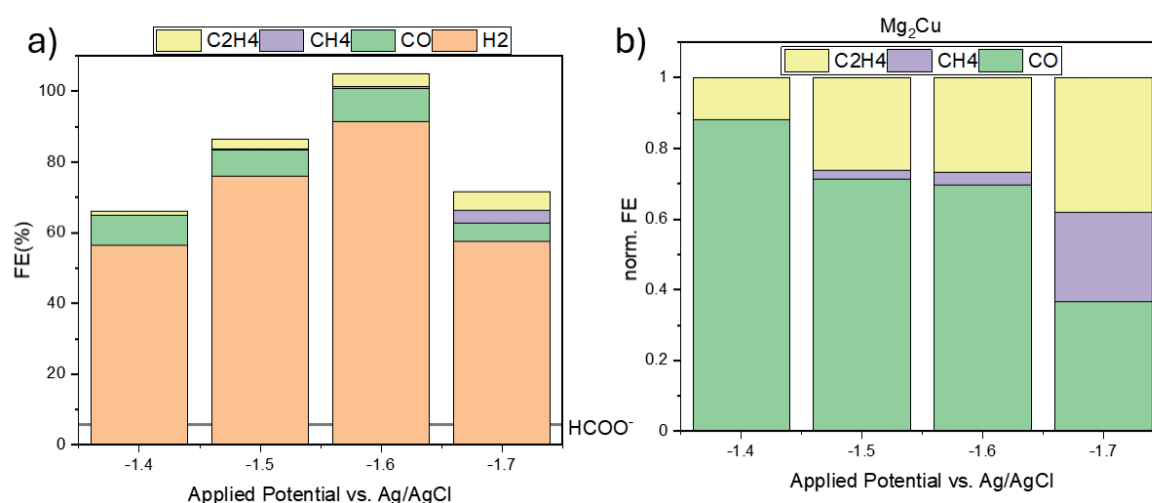


Figure 4: Electrochemical CO_2 reduction on Mg_2Cu catalysts in CO_2 -saturated aq. $KHCO_3$ solution, tested at various potentials with respect to a Ag/AgCl reference electrode. a) Faradaic efficiencies toward gaseous products measured at each potential, as well as the liquid product $HCOO^-$ measured at the end of the experiment. b) Same dataset depicting the fractional distribution of CO_2 -derived gaseous products, revealing potential-dependent selectivity changes.

We additionally studied the effects of modifying Cu by sulfidation to form CuS_x catalysts, as reported recently in Stojkovic et al. 2024. In this case, the alteration of copper led to suppression of $>2 e^-$ products, instead favoring the $2 e^-$ products CO and $HCOO^-$. The selectivity to $HCOO^-$ in particular could reach high values ($>70\%$ FE_{HCOO^-}). Detailed analysis by mass spectrometry and X-ray photoelectron spectroscopy revealed rapid loss of sulfur under electrochemical conditions, but the residual sulfur was stable and crucial for the $HCOO^-$ production, and we found that it correlated with the stabilization of partially oxidized Cu^+ species at the surface.

An additional activity carried out by HZB and KIT-IMVT together with other Helmholtz colleagues was a comparative study to benchmark several electrochemical approaches for converting CO_2 to CO, published recently (Hecimovic et al. 2024). Here, we compared low-temperature, high-temperature, and plasma electrolysis using a set of unified descriptors and KPIs. The result showed the range of technology readiness levels (TRLs) of the three technologies, and highlighted their advantages and disadvantages. We concluded that each approach still shows promise for certain applications and implementations, and continued study of each is needed to bring them to TRLs allowing their direct comparison.

Work Package 2.2: Demonstrator concept for CO₂ cycle with temporary subsurface storage
M-P2.2: Numerical circulation test with supercritical CO₂ as working fluid, under typical reservoir conditions of selected sites and operational scenarios

Within this sub-task, detailed modeling and simulation studies of the energy storage system half-cycle were developed and performed. The basic structure of the modeled system follows [1] as depicted in Figure 5. During times of excess production from renewables, stored CO₂ is back-produced from the subsurface store and used within a Sabatier reactor system for the production of SNG based on electrolytic H₂ from a high temperature electrolyzer. The produced SNG is then stored in a state-of-the-art CH₄ subsurface store for later reconversion. In case of insufficient electricity production from renewables, the stored SNG is fired in the reconversion half-cycle, which is based on a sCO₂ power cycle featuring an Allam Cycle configuration. The required O₂ is provided by a dedicated air separation unit (ASU) and the resulting CO₂ from the combustion reaction is separated from the residual water and is again stored in the CO₂ subsurface store for geothermal heat extraction and reutilization in the SNG production half-cycle.

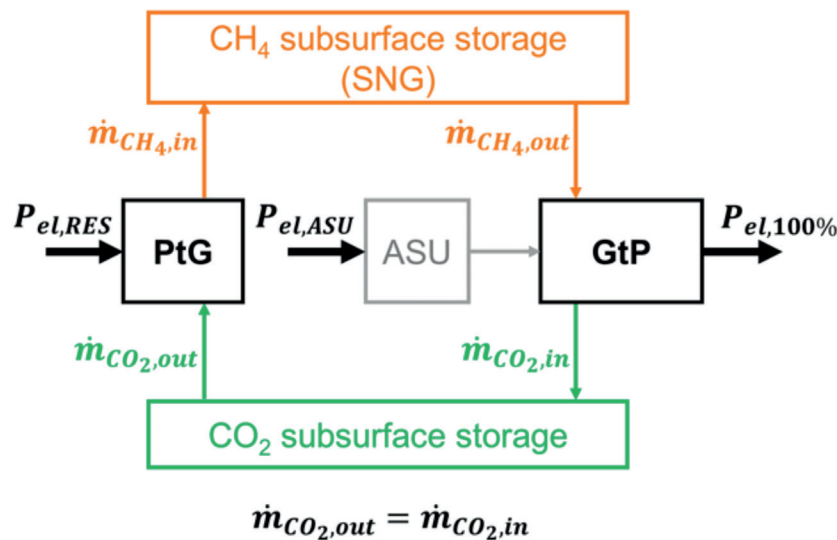


Figure 5: Basic scheme of the energy storage system with subsurface-storage [1].

The system model is comprised of the following component models (alongside their very basic model characteristics):

- the SNG combustor (steady state, adiabatic and stoichiometric combustion),
- the sCO₂ turbine (adiabatic and isentropic expansion),
- the printed circuit heat exchanger (PCHE, spatially resolved 1D model),
- the compressor (multi-stage compression, Balje's curve approach),
- the pump (multi-stage centrifugal pump),
- the air separation unit (ASU, simple lumped approach based in literature performance data),
- the separators (simple black box models),
- the high temperature electrolyzer (including BoP model, based on O²⁻-conducting electrolytes, simple literature model taken from [2]),
- the Sabatier stage (polytropic fixed bed reactor model, discretized axially, kinetics of Koschany et al. [3]).

All relevant thermodynamic properties (enthalpies, thermal conductivities, viscosities, etc.) of the involved fluids were determined based on either REFPROP, COOLPROP, data from NIST or based on [4] with established approaches (Wilke, Brokaw, Wassiljewa, etc.) for mixture properties calculation.

Based on the developed and tested component models, extensive studies with respect to the determination of thermodynamic properties and the consistency and validity of the involved thermodynamic models were carried out for the entirety of the cycle model. Apart from that, the halt cycles were simulated based on typical and representative reservoir conditions. Utilizing the sub-system models of both the P2G and the G2P half-cycles, the numerical circulation test of the subsurface storage system was successfully performed. Moreover, the retrieved system simulation data was used to also determine the techno-economic performance of the respective sub-systems (as part of M-P2.5).

To identify suitable CO₂ emitters for the initial storage filling and plume establishment phase, an extensive data collection was performed based on the data available in the Emissions Trading System (ETS) of the European Union [5]. The relevant data is contained within the European Union Transaction Log (EUTL), which is run by the European Commission. The available data was enhanced to feature all geolocations of all listed stationary emitters to allow for a spatial assessment of the storage potential and emission reutilization potential within the borders of Germany. Core information on the operating entities, the emitting entities and ultimately the CO₂ emission quantity for the year 2023 were compiled for the subsequent analysis. The collected emitters were selected and grouped by their industrial activity based on the allocated activity code. Figure 6 shows the emitters identified for Germany (emission threshold of 50 kt/a and without emissions from combustion of fuels for the provision of heat and electricity) for the year of 2023.

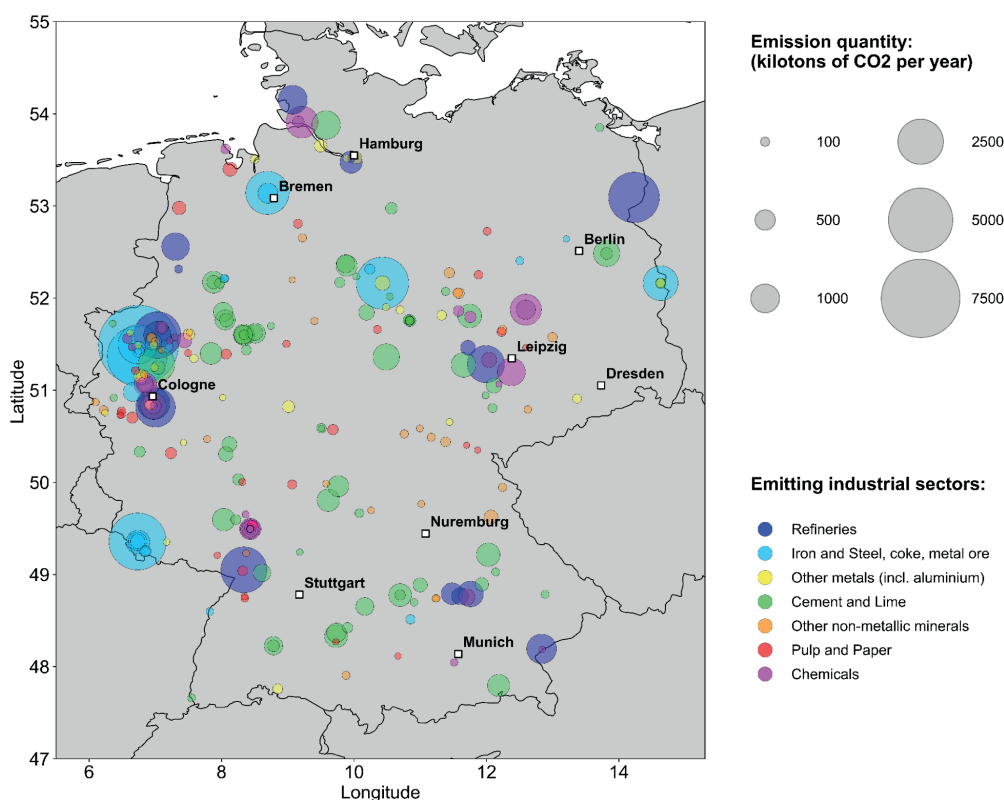


Figure 6: Identified emitters and emission quantities for Germany in 2023.

The emitters are clustered with respect to their distance to each other to identify regions and industrial sites with clear synergies concerning CO₂ transport and handling. This information is particularly valuable in relation to the location of suitable subsurface storage features (porous aquifers, salt formations/caverns, etc.). Within the conducted studies, the emitter cluster locations were put in relation to potential subsurface storage sites in Germany as depicted in Figure 7.

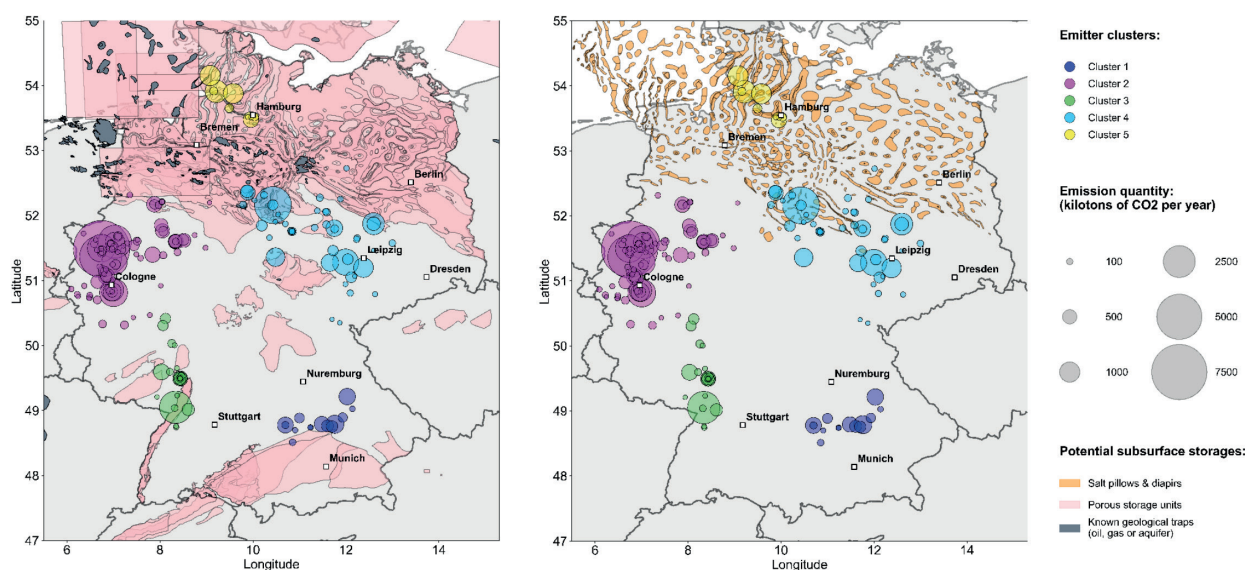


Figure 7: Emitter clusters and potential subsurface storage locations in aquifers (left) and salt formations (right) alongside emission quantities for Germany in the year of 2023.

Within this sub-task, beneficial CO₂ emitter clusters and suitable storage locations in the north and south of Germany were successfully identified. The gathered data and findings will be employed in future system assessments of the closed energy storage system.

The main work conducted in M-P2.2 was successfully completed within the first 10 months of the project (modeling and setup of the numerical circulation test based on sCO₂ for fixed subsurface and operational conditions). However, the selection of suitable sites and the collection of suitable industrial CO₂ emitters within Germany and Europe was finished later in project month 18.

M-P2.5: Demonstrator concept for subsurface CO₂ cycle derived

Based on the work performed within M-P2.2, a demonstrator concept for large-scale reconversion cycles has been successfully developed. Figure 8 depicts the employed structure of the considered sCO₂ reconversion cycle.

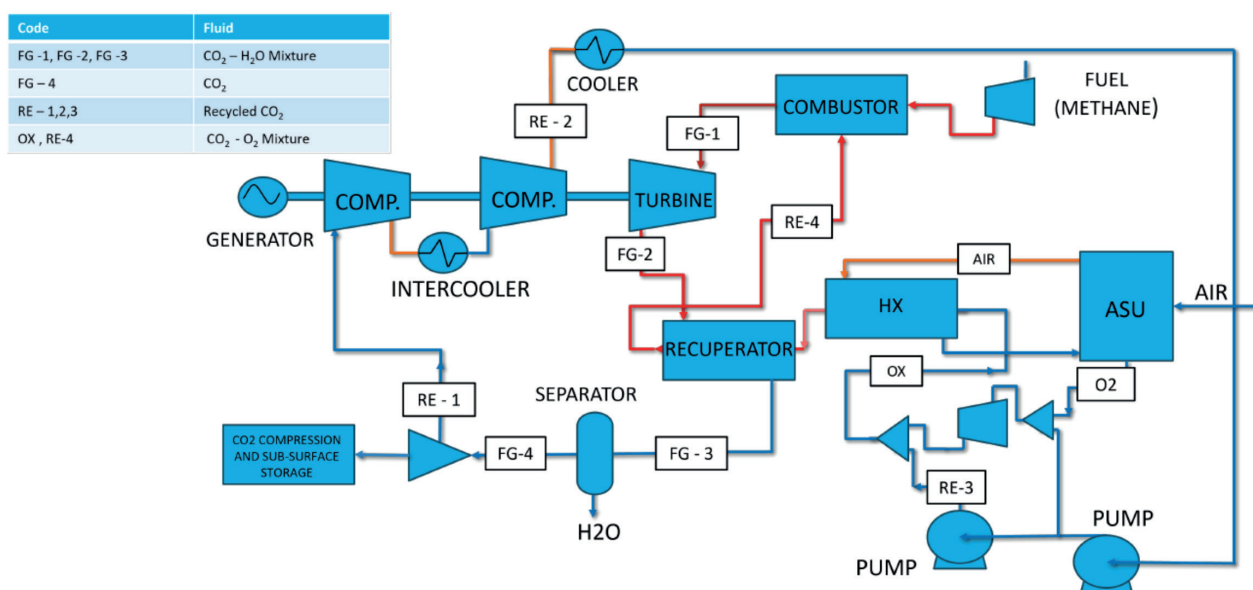


Figure 8: Basic scheme of the sCO₂ power cycle design.

Utilizing the models developed in the first period of this project (M-P2.2) detailed operational and economic characteristics of the system concept were derived by the likes of:

- heat integration studies for the Sabatier SNG system (Pinch-Point Analysis),
- assessment of different operation modes of the electrolyzer and its impact on the sub-system efficiency,
- detailed reactor performance studies to ensure high conversion, yield and selectivity,
- techno economics and production cost assessment of the SNG production step,
- detailed thermodynamic assessments/studies of the sCO₂ reconversion cycle and
- basic techno-economics of the sCO₂ reconversion cycle.

Figure 9 depicts the simulated basic performance and techno-economic characteristics of the sCO₂ cycle. The project studied the impact of several core operational parameters, such as the compressor output temperature and the turbine inlet pressure, on the reconversion cycle efficiency and levelized cost of electricity of the demonstrator concept.

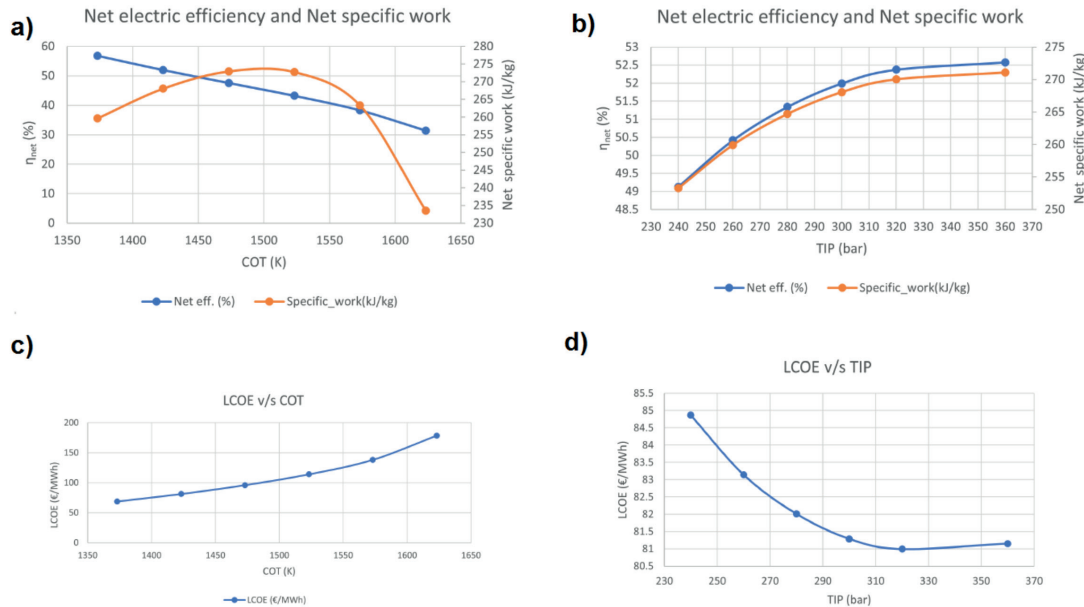


Figure 9: Performance characteristics of the $s\text{CO}_2$ cycle for a) the variation of the compressor outlet temperature (COT), b) the variation of the turbine inlet pressure (TIP) as well as the derived levelized cost of electricity in dependence of c) the COT and d).

In addition to the numerical and simulative demonstrator concept assessment, the experimental $s\text{CO}_2$ facility CARBSOLA was established and commissioned at the Institute of Fluid Dynamics at HZDR. In order to demonstrate $s\text{CO}_2$ cycle concepts and to validate all involved technical components, a demonstrator with a power of 20 kW was designed, erected, commissioned and successfully operated at HZDR. The facility is partially housed indoors (approx. 6.0 m × 4.3 m × 4.8 m) and outdoors. The facility's components and piping are thermally insulated (indoor sections) to minimize heat losses and prevent condensation. The experimental facility can be seen in Figure 10. The experimental $s\text{CO}_2$ facility was successfully tested and commissioned within the project period. Numerous measurement points were established throughout the cycle setup to measure temperatures, pressures, flow velocities and mass flow rates.

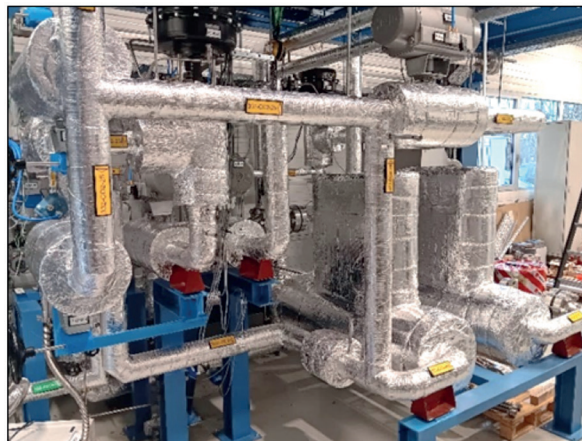


Figure 10: Experimental $s\text{CO}_2$ cycle at HZDR.

The setup is comprised of the main cycle components, namely the pump, the expansion device and the heat exchangers. The installed piston pump is able to convey 180 kg/h of liquid CO₂ leading to a maximum pressure of 250 bar. The suction line and the pistons of the pump are air cooled to ensure liquid suction at the inlet of the pump and manageable piston temperatures. Valves actuated by pressurized air (DN 25 PN400 control valves) are employed as expansion device in the sCO₂ cycle. Two heat exchangers are included in the cycle – a printed-circuit heat exchanger and a typical rod-bundle heat exchanger.

The development of the demonstrator concept and the commissioning of the experimental facility CARBOSOLA were successfully accomplished within the given project period in month 24 of HI-CAM phase 2.

REFERENCES

- [1] S. Fogel, C. Yeates, S. Unger, G. Rodriguez-Garcia, L. Baetcke, M. Dornheim, C. Schmidt-Hattenberger, D. Bruhn, and U. Hampel, “SNG based energy storage systems with subsurface CO₂ storage,” *Energy Adv.*, vol. 1, pp. 402–421, 2022.
- [2] F. Petipas, A. Brisse, and C. Bouallou, “Model-based behaviour of a high temperature electrolyser system operated at various loads,” *Journal of Power Sources*, vol. 239, pp. 584–595, 2013.
- [3] F. Koschany, D. Schlereth, and O. Hinrichsen, “On the kinetics of the methanation of carbon dioxide on coprecipitated nial(o)x,” *Applied Catalysis B: Environmental*, vol. 181, pp. 504–516, 2016.
- [4] B. Todd and J. Young, “Thermodynamic and transport properties of gases for use in solid oxide fuel cell modelling,” *Journal of Power Sources*, vol. 110, no. 1, pp. 186–200, 2002.
- [5] EU Emissions Trading System (EU ETS), 2024: Union Registry – European Commission (europa.eu)

SPECIAL FEATURES

Work Package 2.1: Electrocatalytic CO₂ conversion

The project facilitated exchange between HZB, KIT-IMVT, and Hereon on the topic of CO₂ electrolysis. HZB and IMVT carried out reciprocal site visits in 2024 to learn about methodologies and reactor designs, and to conduct joint experiments. Hereon fabricated the alloy catalyst materials which were tested at HZB, a collaboration which will continue. HZB, IMVT, and other Helmholtz colleagues jointly prepared a benchmarking paper (Hecimovic 2024) which compares promising approaches to electricity-driven CO₂ utilization.

Work Package 2.2: Demonstrator concept for CO₂ cycle with temporary subsurface storage

The performed systemic studies on large-scale subsurface storage systems are pivotal in view of achieving a net-zero, alternative electricity supply on large scales and a fully circular use of CO₂ and fluctuating renewable generation capacities. The aforementioned characteristics also align well with the overarching goals of the Helmholtz Association with respect to resource and energy efficiency. The one of a kind experimental facility CARBOSOLA will elevate the research on supercritical CO₂ cycles for power generation in Europe and is therefore a key strategic advantage of the HZDR and therefore the Helmholtz Association.

OUTLOOK ON FUTURE WORK

Work Package 2.1: Electrocatalytic CO₂ conversion

HZB and IMVT first connected in HI-CAM and are now continuing to work together on various projects, including both CO₂ capture (DACStorE) and CO₂ conversion. HZB and Hereon will continue joint study of metal alloy materials for use as electrocatalysts.

Work Package 2.2: Demonstrator concept for CO₂ cycle with temporary subsurface storage

The described work on energy storage systems based on subsurface storage and supercritical CO₂ in a closed-system approach will be continued and employed as a starting point for future projects. Moreover, different storage system concepts different to the one developed within HI-CAM are and will be investigated in the future with international partners throughout Europe. The experimental facility CARBSOLA will be employed in a large variety of projects dealing with thermal energy storage and the characterization of sCO₂ cycle operation with international and industrial partners, acting as a European beacon of sCO₂ experiments.

PUBLICATIONS

- **Unintended cation crossover influences CO₂ reduction selectivity in Cu-based zero-gap electrolyzers**
El-Nagar et al. Nature Communications
 Nature Communications, 2023, 2062
- **Benchmarking microwave-induced CO₂ plasma splitting against electro chemical CO₂ reduction for a comparison of promising technologies**
Hecimovic et al., J. CO₂ Util.
 ScienceDirect, 2024, 83, 102825
- **Techno-economic assessment of methane-fired sCO₂ power cycle layouts incorporating CO₂ separation and storage**
J. Rathod
 Master thesis, May 2024, Indian Institute of Technology Jammu (IIT). (Supervised Master Thesis)
- **Large scale energy storage systems based on SNG and subsurface carbon dioxide storage**
S. Fogel, S. Unger, and U. Hampel
 Helmholtz Energy Conference, Koblenz, Germany, 12.-13.06.2023. (Poster Presentation)
- **Robust and efficient electroreduction of CO₂ to CO in a modified zero-gap electrochemical cell**
Siyu Zhong, etc.
 Chemical Engineering Journal, under review
- **Synergistic electroreduction of CO₂ to C1-C3 gas products in a pressure-tolerant MEA system in preparation**
Siyu Zhong, Wenwu Yang, Sida Liu, Roland Dittmeyer

- **Techno-economic assessment of CO₂ methanation processes for energy storage applications**
S. Naik
Master thesis, May 2024, Indian Institute of Technology Jammu (IIT). (Supervised Master Thesis)

- **Facile Synthesis of Cu_xS Electrocatalysts for CO₂ Conversion into Formate and Study of Relations Between Cu and S with the Selectivity**
Stojkovikj et al.
Adv. Func. Mater., 2024, 2415405

- **Experimental Investigation of the Production Cycle in a CO₂ Based Electrothermal Energy and Geological Storage System**
S. Unger, S. Fogel, P. Schütz, R. Chacartegui, A. Carro, M. P. Farkas, C. Schmidt-Hattenberger, and U. Hampel
The 6th European sCO₂ Conference for Energy Systems, Delft, The Netherlands, 09.04.-11.04.2025.
(Oral Presentation – submitted)

- **The sCO₂ facility CARBOSOLA: Design, purpose and use for investigating geological energy storage cycles**
S. Unger, S. Fogel, P. Schütz, R. Chacartegui, A. Carro, J. Carneiro, and U. Hampel
Proceedings of ASME Turbo Expo 2024: Turbomachinery Technical Conference and Exhibition, Contribution GT2024-122133, 2024. (Proceeding Paper)

- **Supercritical CO₂ cycle for sensible thermal energy storage and power generation applications**
S. Unger, S. Fogel, M. B. Mohankumar, A. F. Guille-Bourdas, P. Schütz, and U. Hampel
Helmholtz Energy Conference, Koblenz, Germany, 12.-13.06.2023. (Oral Presentation)

- **The sCO₂ facility CARBOSOLA: Design, purpose and use for investigating geological energy storage cycles**
S. Unger, S. Fogel, P. Schütz, R. Chacartegui, A. Carro, J. Carneiro, and U. Hampel
ASME Turbo Expo 2024: Turbomachinery Technical Conference and Exhibition, London, United Kingdom, 24.-28.06.2024. (Oral Presentation)

- **Experimental Investigation of the Production Cycle in a CO₂ Based Electrothermal Energy and Geological Storage System**
S. Unger, S. Fogel, P. Schütz, R. Chacartegui, A. Carro, M. P. Farkas, C. Schmidt-Hattenberger, and U. Hampel
Proceedings of the 6th European sCO₂ Conference for Energy Systems, 2025.
(Proceeding Paper – submitted)

CLUSTER I: **NET-ZERO-2050**

Project 3

Peatland Rewetting as a Natural Climate Solution

AUTHORS

Helmholtz-Zentrum
Potsdam
Deutsches
GeoForschungsZentrum
(GFZ)
Torsten Sachs

German Aerospace Center
(DLR)
Yvonne Scholz

Centers involved:



SUMMARY

Based on interest communicated to us from the City of Potsdam administration, the original objective at the time of application was to co-design a GHG monitoring concept for the pre- and post-rewetting phases of a peatland rewetting project within the Potsdam city limits. The design was to include the site selection in an iterative process with all relevant actors, technical and infrastructural assessments, and, originally, an a priori estimate of emission reduction potential in order to prioritize the assumed multiple candidate sites.

During the initial meeting with representatives of both the City of Potsdam and the Brandenburg State Agency for the Environment (LfU), it became clear that the short life-time of HICAM makes it unrealistic to achieve any real-world results when starting a peatland rewetting project from scratch as envisioned in the proposal, given the complex and long administrative and stakeholder processes. A much more pragmatic approach was needed and became available when LfU asked GFZ to implement a GHG monitoring for a recently started rewetting project in Brandenburg. Thus, site selection was expanded to the entire State of Brandenburg and prior work by LfU, particularly relating to logistical feasibility (based on ownership and openness of the relevant actors to participate) trumped reduction potential as the main criterion for site selection.

Iterative discussions and multiple site visits eventually resulted in the identification of monitoring locations in four sites slated for rewetting whose paludiculture use will be biomass harvesting, water buffalo grazing, cattle grazing, and a mixed use depending on the actually achieved water levels. One site will serve as a before-after case (or remain drained in a worst case development), one is already in a test rewetting stage with elevated water levels, two will be certain before-after cases, and a fifth site will certainly remain drained and serve as a direct control site. GHG monitoring concepts were designed for all sites and an additional project proposal with a consortium extending beyond HICAM was submitted and approved, with funding for the actual measures and extensive monitoring secured until >2030.

In a modelling approach, we also assessed the potential biomass yield from paludiculture and its energy potential. Power generation in combined heat and power plants could satisfy between 0.7 % and 3.7 % of the German gross electricity demand. It thus cannot be a major player like the solar and wind resource can, but it might contribute to a backup solution in extreme weather situations.

ACHIEVED RESULTS

Work Package 3.1: Co-design of the GHG monitoring

The starting point for the monitoring design was the site selection based on the State Agency for the Environment's (LfU) long-term planning and its expertise regarding regional conditions, such as the ownership status of potential candidate sites and the owners' and users' openness to rewetting measures. Primary search areas were the Rhinluch/Havelland region, the Uckeratal and Randowbruch, the Spreewald, and the Mittlere Havel between Potsdam and Brandenburg (Figure 1). One site at Möllmer Seewiesen near Oranienburg was already set by LfU and a test phase for raised water levels had already started. The search areas included hydrogenetic peatland types typical for Brandenburg, different water (management) regimes, peatland characteristics, and potential biomass utilizations as summarized in Table 1.

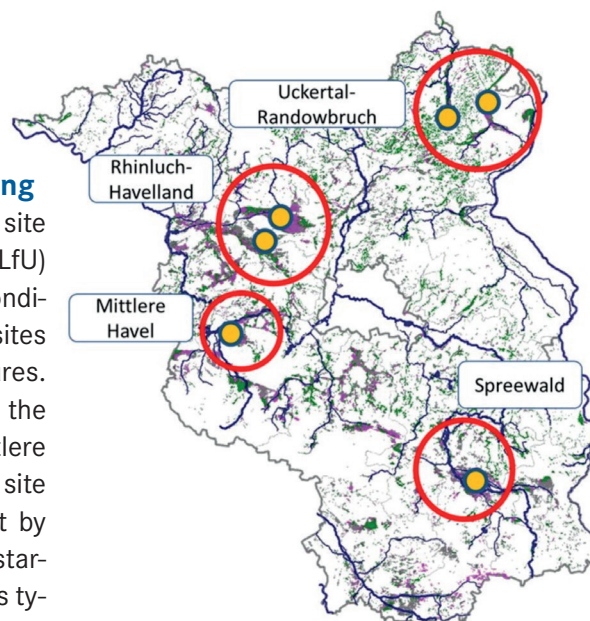


Figure 1: Search areas.

Given its many advantages (e.g. non-disturbing for the system under investigation, integration across small-scale heterogeneities, continuous high-frequency measurement, level of standardization in the community, etc), the eddy covariance (EC) method was determined to be the state-of-the-art method for GHG monitoring in all peatland rewetting projects that explicitly include a monitoring and reporting component. Enclosure-based methods can complement EC based monitoring where useful, in particular if a detailed spatial resolution or GHGs such as N_2O are of interest.

Region	Rhinluch / Havelland	Mittlere Havel	Uckeratal / Randowbruch	Spreewald
Original hydrogenetic peatland types	Paludification mire	Paludification mire and floodplain inundation mire	Percolation and paludification mire	Floodplain inundation mire
Water regime type	topogenic water regime	Floodplain inundation regime (controlled)	Percolation regime	Floodplain inundation regime (controlled)
Characteristic peatland composition	Shallow peat on sand	Thin peat on deep calcareous mud	Thick peat on calcareous mud	Silicate rich thin peat on sand
Potential area with raised water levels				
already wet (ha)	0	77	310	973
until 2026 (ha)	310	289	177	0
until 2028 (ha)	0	247	47	0
Expected dominant vegetation species at high water levels	Reed canary grass, sedges	Reed, <i>Bolboschoenus</i> , <i>Glyceria maxima</i>	Sedges, reed, species-rich herbaceous cover	Reed canary grass, reed-sedge mixed stands
Biomass use	Substrate, organic fertilizer, pellets	Biogas, biochemicals, biorefinery	Construction and insulation materials, biochar	Thermal utilization, compost, organic fertilizer

Table 1: Characteristics of the search areas.

After identifying candidate sites within the regions, further screening included the following criteria:

- The area of the vegetation/groundwater combination to be examined must be larger than the EC measurement footprint, flat, and free of flow-distorting elements in the landscape
- Land users and owners must agree to the long-term installation of measuring technology
- Dominant soil types must be degraded fens (no “Anmoor” or “Moorfolgeboden”)
- Annual average groundwater level has already risen again or will be raised within a project lifetime, can be regulated, and its changes can be clearly recorded
- For multi-site monitoring, significant site differences should exist in terms of water management and vegetation composition
- Optional: availability of line power

Iterative discussions and multiple site visits eventually resulted in the identification of the following sites for the LfU-led BLuMo-project, for which GFZ was contracted to implement the GHG monitoring:

- Hakenberg/Rhinluch: depending on permitting progress, this site will become wet within the next years and therefore constitutes a before-after case with continued biomass harvesting (dominantly reed canary grass and tall sedges).
- Dameswalde/Möllmer Seewiesen: constitutes a post-rewetting case, as a preliminary water level increase is already underway and will simply become turn into the permanent level eventually; paludi culture use will be water buffalo grazing.
- Blumberg/Randowbruch: constitutes a mostly before-after case with rewetting decision finalized and an initial water level increase already caused by beaver activity; paludiculture use will be a mix of continued cattle grazing and biomass harvesting depending on final water levels.

A similar site selection process was followed for the BMEL-funded WetNetBB project, albeit with additional stakeholder involved from Thünen, HNEE, and ZALF and the additional objective to identify a site-pair (raised water level vs. continued drainage as a control site, with otherwise similar characteristics), which proved exceedingly difficult.

A common monitoring and power supply system was designed for all sites to ensure comparability and allow for implementation of community standards. GHG and biometeorology instrumentation additionally follows ICOS recommendations and data processing, and qa/qc procedures are being unified across multiple peatland project consortia in all five peatland-rich federal states. Power supply systems are based on solar power and battery storage and backed up by fuel cells in exceptionally long “dark” periods, primarily in winter. The compact design reduces the infrastructure footprint to a raised wooden platform of 2 m x 6 m. At sites with cattle or buffalo grazing, the platforms are fenced off.

Work Package 3.2: Assessment of biomass yields

While rewetting drained peatlands reduces CO₂ emissions and eventually leads to CO₂ uptake, in most cases a continued agricultural use (“paludiculture”) is needed in order to provide a livelihood for landowners and users. Various forms of paludiculture can be a viable economic alternative on sites with raised water levels. Paludiculture has mostly been investigated in field experiments. As Wichmann (2017) shows, revenues for farmers are highest when the products can be sold as building material (e.g., thatching reed or insulation). They are lower but predominantly positive in case of energy use through combustion. In case of anaerobic digestion for biogas production, the revenues are mostly negative. At DLR, we investigated how much power and heat can be generated from paludiculture crops in Germany.

To quantify the potential contribution to energy supply, we estimate the amount of biomass that could be harvested from paludiculture in Germany and how much power and heat might be generated from it. The estimation of the biomass potential from paludiculture involves the choice of an example crop, a literature review of the corresponding yields, information gathering on calorific values, harvesting and combustion efficiencies, and finally processing of these parameters in combination with the Global Peatland Map 2.0. Here, we chose common reed (*phragmites australis*) as an example of an energy crop that can grow on rewetted peatland. Since according to Wichmann (2017), biogas production is seldomly profitable, we consider only combustion in combined heat and power (CHP) plants. Table 2 shows the parameters for the biomass potential estimate extracted from the platform.

Table 2:

Yield and calorific values for common reed (*Phragmites australis*).

Sources: Moorwissen.de (a), 2019¹; Moorwissen.de (b), 2019².

	low	medium	high
yield in t _{TM} /ha/a	3,6 ¹	9,3	15 ¹
Calorific value in MJ/kg	14,5 ² (15% Feuchte)	16,5	18,5 ¹

Table 4: Peatland area, potential common reed yield, energy potential and power and heat generation potentials in the German federal states.

		Common reed (phragmites australis)			
	Peatland area in km ²	Yield in kt/a	Energy potential in GJ/a	CHP power generation potential in GWh _{el} /a	CHP heat generation potential in GWh _{th} /a
Baden-Württemberg	399	371	5202	289	867
Bayern	1940	1804	25300	1406	4217
Berlin	3	3	41	2	7
Brandenburg	2163	2012	28217	1568	4703
Bremen	55	51	721	40	120
Hamburg	31	29	404	22	67
Hessen	63	58	818	45	136
Mecklenburg-Vorpommern	2318	2156	30233	1680	5039
Niedersachsen	5681	5283	74101	4117	12350
Nordrhein-Westfalen	392	365	5114	284	852
Rheinland-Pfalz	47	43	610	34	102
Saarland	13	12	171	9	28
Sachsen	242	225	3154	175	526
Sachsen-Anhalt	757	704	9874	549	1646
Schleswig-Holstein	1327	1234	17312	962	2885
Thüringen	5	5	71	4	12
Summe	15436	14356	201342	11186	33557

Table 5: Peatland area, common reed biomass yield, corresponding energy potential and combined power and heat generation potentials in Germany.

	Peatland area in km ²	Yield in kt/a	Energy potential in GJ/a	CHP power generation potential in GWh _{el} /a	CHP heat generation potential in GWh _{th} /a
Min		5557	68492	3805	11415
Mean	15436	14356	201342	11186	33557
Max		23155	3641089	20228	60685

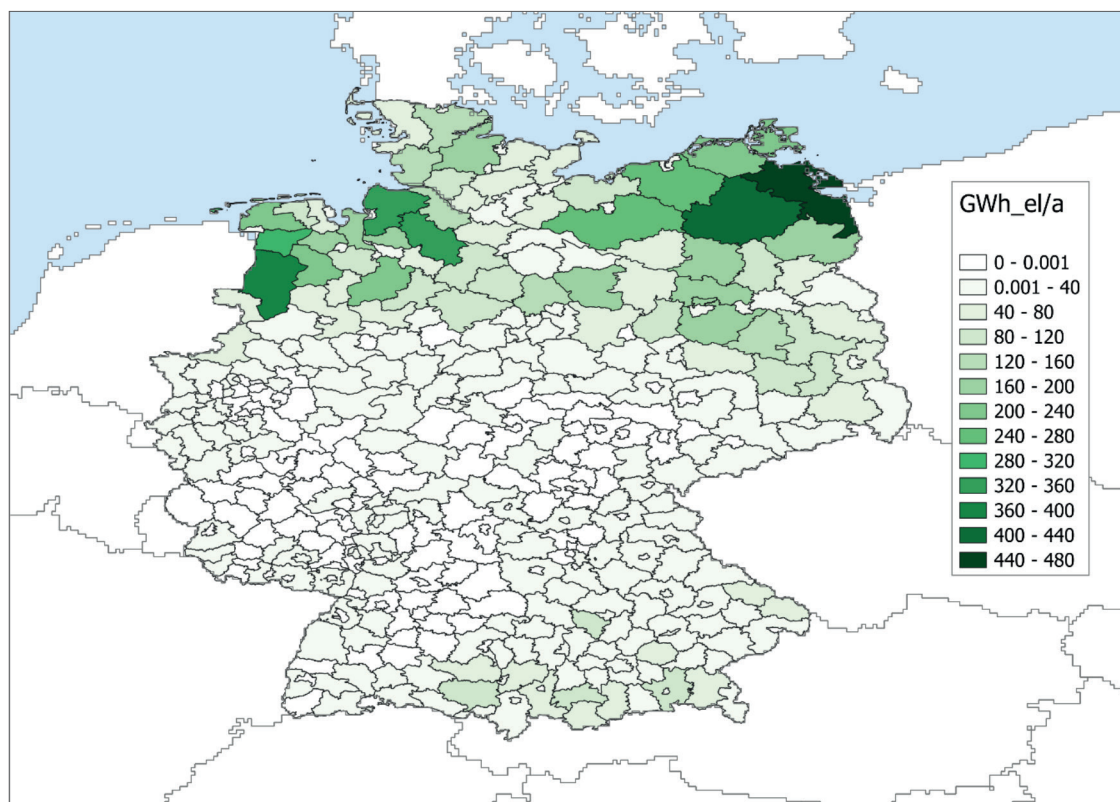


Figure 2: Power generation potential of common reed combustion in CHP plants in Germany, assuming combustion close to the peatland areas.

Work Package 3.3: Synthesis of full demonstrator concept

This WP constitutes a somewhat artificial separation from WP3.1 as it was envisioned to synthesize work from WP3.1 and produce a white paper or project proposal. As indicated in the summary, the developed GHG monitoring concepts as described in WP3.1 above were immediately integrated into a (successful) project proposal. Therefore, no additional white paper was produced.

OUTLOOK ON FUTURE WORK

At GFZ, the HI-CAM (and TERENO-related) work directly resulted in joining a consortium of ATB, ZALF, LfU, and HNEE and the joint design and implementation of the BMEL funded project “WetNetBB - Management and biomass utilization of wet fens: Network of model and demonstration projects in peatland regions of Brandenburg” of which GFZ leads the subproject for GHG flux monitoring. In addition, we were tasked by LfU to implement and execute the GHG monitoring for a BMUV funded sister project, resulting in a network of five new long-term sites for pre- and post-rewetting monitoring of GHG in agriculturally used fens. On a larger scale, 2024 saw the establishment of the “PaludiNet” aimed at harmonizing monitoring and data treatment approaches across all five peatland-rich federal states. The next ten years will thus provide an unprecedented stream

of standardized GHG monitoring data from a wealth of newly established and representative peatland sites with multiple treatment combinations in terms of water level increase and paludiculture use that will allow for a comprehensive assessment of the actual rewetting effect on GHG dynamics in relation to management.

This estimation of paludiculture energy potentials in Germany is a first rough assessment to get an idea of a potential contribution to energy supply. The assessment can be improved by considering more species, using more exact land cover data and precise information on the share of rewetted areas actually usable for paludiculture. Further important analyses should investigate possible combinations of paludiculture and PV or wind power generation and the resulting revenues for farmers.

EVENTS

— 1. Moore in Potsdam – Vernetzung Wissenschaft & Praxis

Organizers: Claudia Rose, Koordinierungsstelle Klimaschutz; Torsten Sachs, GFZ

Date: 04.07.2022

Format: Online

Participants:

Prof. Dr. Susanne Liebner, GFZ

Prof. Dr. Torsten Sachs, GFZ

Dr. Lukas Landgraf, LfU, Abt. Wasserwirtschaft, Moorschutzprojekte

Christina Grätz, Geschäftsführerin NagolaRE GmbH

Ralf Voigt, Landeshauptstadt Potsdam, Untere Wasserbehörde

Claudia Rose, Landeshauptstadt Potsdam, Koordinierungsstelle Klimaschutz

— 2. Site selection visits

Organizers: Anje Marten, LfU; Torsten Sachs, GFZ

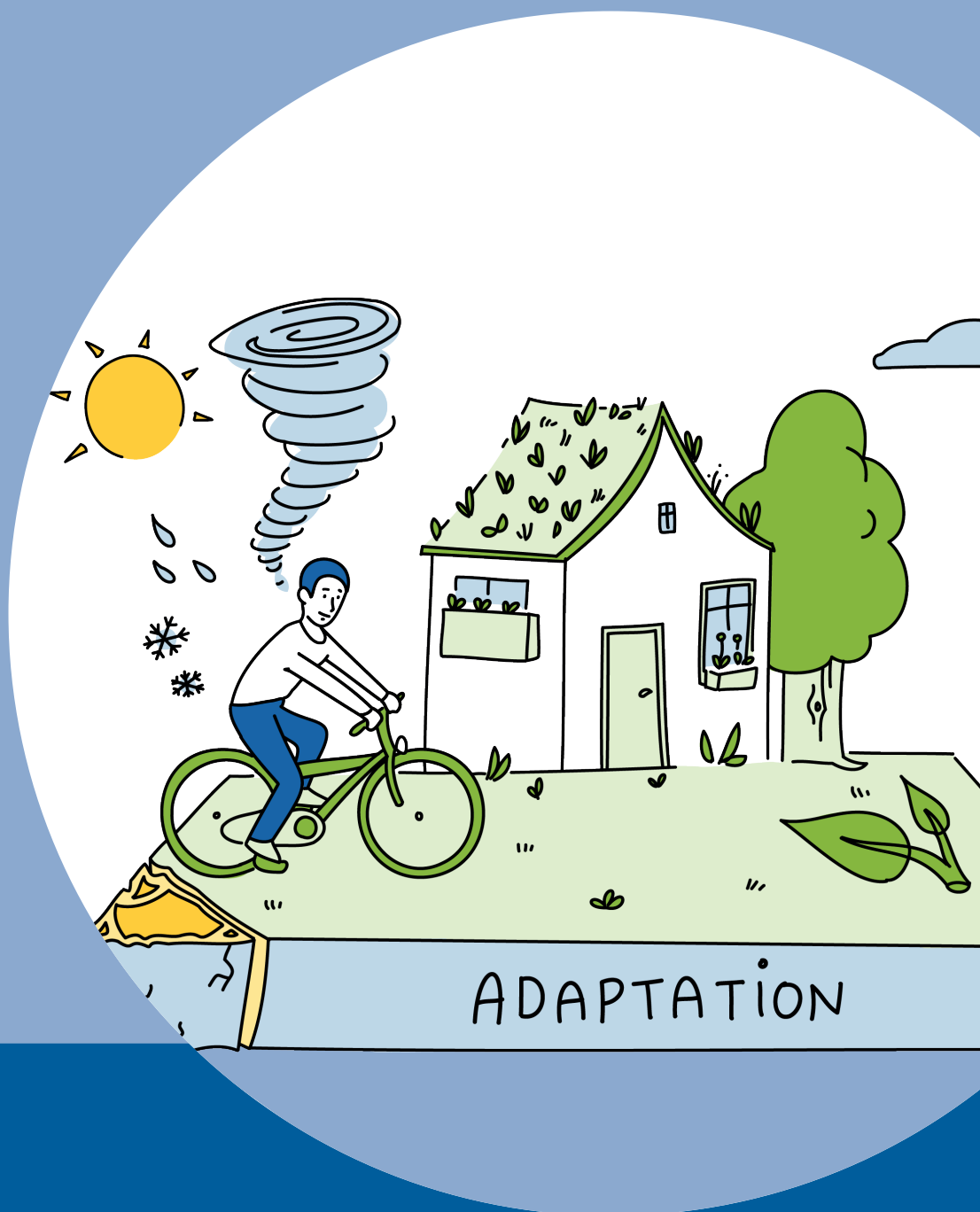
Date: 06.07.2022, several follow-up visits at different sites

Format: on-site visits

Participants:

Anje Marten & Geraldine Knopf, LfU

Torsten Sachs & Christian Wille, GFZ



CLUSTER II

Cluster II: Introduction

Lead: Attinger, S.¹

Co-ordination: Marx, A.¹

Affiliation(s): ¹ Helmholtz-Centre for Environmental Research (UFZ),

Computational Hydrosystems (CHS), Leipzig, Germany

Email (Corresponding Author): sabine.attinger@ufz.de

In phase 1, Cluster II of the Helmholtz Climate Initiative, we showed how a mission-oriented amalgamation of different model-components from 9 different Helmholtz centers in 4 Research Areas, each one representing a specific expertise, can lead to model-chains with significant added-value.

Examples are model chains running from extreme atmospheric jetstream scenarios, through high-resolution hydrological surface water simulations to assessments of crop yield or heat-stress in urban areas. The phase 1 model-chains serve now as the basis for the development of a new generation of high-resolution near real-time impact-assessment and management systems of unprecedented quality at national or even European scale.

In phase 2, Cluster II has selected project initiatives which can move now to the next step, i.e. from high-resolution real-time simulations to actual forecasts. The mission was to develop hydro-meteorological model-chains that in the hydrological domain provide a realistic high-resolution flood-forecasting for small catchments and, for limited domains, even a hydraulic forecasting to serve in early warning systems for events like in the Ahrtal in June 2021.

The team has created a high-resolution, impact-based flood forecasting and early warning system. This cutting-edge system relies on in-house models, including the hydrologic model mHM and the hydrodynamic model RIM2D, to provide a seamless forecasting chain. A major strength of this approach is its capacity to rapidly simulate the entire flood forecasting process - from the initial meteorological event to the resulting flood inundation and potential impacts - in near real-time, with processing times significantly faster than the forecast horizon.

In addition, the Ahr flood exposed a significant weakness and emphasized the pressing need to gain a deeper understanding of how extreme floods are affected by changes in rainfall patterns and intensity due to climate change, but also their connection to broader weather systems. To examine these relationships, the team developed counterfactual scenarios that involve shifting extreme precipitation events to different locations within small to medium-sized river basins. Additionally, a statistical analysis to explore the year-to-year variability of convective events and their association with large-scale weather patterns was performed.

Moreover, the researchers developed a storyline approach. In that approach, they used hypothetical climate scenarios to analyze how particular events, such as heatwaves or marine heatwaves, might change under various climate conditions, including those of the past, present, and future. Building on previous studies that primarily utilized low-resolution models, this report delves into the benefits of incorporating high-resolution

models with kilometer-scale precision to improve the accuracy and physical realism of climate projections. In the health field, we have provided forecasts with respect to heat stress, something becoming increasingly important with the increased heating of our urban areas. Health research has undergone a significant transformation, shifting its focus from individual risk factors to a more comprehensive understanding of health within the broader context of natural systems. This new approach has been formalized in a generalized health model, which has led to the development of an interactive toolbox. A key component of this toolbox is the ability to simulate heat stress in urban areas with high temporal and spatial resolution. To make this toolbox more accessible, a publicly available web application has been designed to support municipal climate adaptation efforts and provide a powerful analysis tool for understanding local thermal conditions.

All together this chapter comprises the expertise from five Helmholtz centers from the research fields “Earth and Environment” as well as “Health”.

CLUSTER II: ADAPTATION

Centers involved:



Counterfactual scenarios and large-scale weather regimes for extreme rainfall events over Germany

Authors: Pandey, P., Kunz, M., Augenstein, A.

Affiliation(s): Karlsruhe Institute of Technology (KIT)

Email (Corresponding Author): michael.kunz@kit.edu

INTRODUCTION

Recent studies have shown significant changes in the occurrence and characteristics of floods across Europe (Fang et al., 2024). These changes have been linked to a range of contributing factors, including increased moisture in the lower troposphere, regional shifts in rainfall patterns, and evolving weather regimes (Mohr et al., 2021). Such alterations in precipitation-generating processes can lead to fluctuations in the frequency and intensity of river floods (Tarasova et al., 2023). Small-to-medium-sized catchments are particularly affected by these changes as they are highly sensitive to localized precipitation extremes. The devastating floods that struck Central Europe in July 2021 highlighted this vulnerability and underscored the urgent need to better understand the sensitivity of extreme floods to changes in rainfall distribution and intensity as well as the relation to large-scale weather patterns (Mohr et al., 2023; Ludwig et al., 2023). To explore this sensitivity, counterfactual scenario analysis has emerged as a valuable tool (Montanari et al., 2023). Building on recent advancements, our study has developed and applied counterfactual scenarios by spatially shifting extreme precipitation events across small-to-medium-sized catchments in Germany. To further investigate the annual variability of convective events, we conducted a statistical analysis of their relationship with large-scale weather patterns that act as key drivers.

DATA AND METHODS

The quantified rainfall scenarios are based on RADKLIM (RAD-KLIM v2017.002) gridded hourly rainfall data provided by the German Weather Service (DWD) for the period from 2001 to 2020 (Winterrath et al., 2019). The spatial coverage of the data is 1100 x 900 grid points with spatial and temporal resolutions of 1 km² and 1 hour, respectively. The hourly data were aggregated into different durations such as 2-hr, 6-hr, 12-hr and 24-hr. The detailed characteristic of the four catchments selected as test cases are provided in Table 1.

To identify the spatio-temporal evolution of extreme precipitation events (EPEs), we defined them as the 100 highest daily rainfall amounts recorded at each grid point for the period 2001-2020. Based on the sample, Type I Extreme Value Distribution, also known as the Gumbel distribution, was applied to the sample at each individual grid point to estimate rainfall totals for specific return periods and rainfall duration (i.e., intensity-frequency-duration curves, IDF). The maximum likelihood method was used to estimate the parameters of the Gumbel distribution.

To construct the counterfactual scenarios, we applied a spatial-shifting approach to the observed EPEs. This approach is grounded in the plausibility of convective rainfall processes, which are characterized by a large stochastic component that can vary significantly over short distances. We first identified EPEs at each grid point for all catchments during the investigation period. For each grid point, we further identified the maxi-

mum 10 (5, or 20) rainfall events and conditionally replaced them with the maximum 10 (5, or 20) events from neighboring regions spanning to distances of 20, 50, and 100 km. After applying the spatial shift at each grid point, the newly generated rainfall values represent the counterfactual rainfall scenarios.

The investigation of a potential relationship between large-scale weather patterns and convective events requires an investigation area larger than Germany. Therefore, we extended our analysis to include cloud-to-ground (CG) lightning data from the EUCLID lightning detection network, covering the period 2001–2021 (May to August) over Western and Central Europe. To identify spatio-temporally intense lightning activity, we applied the Spatio-Temporal Density-Based Spatial Clustering of Applications with Noise (ST-DBSCAN) algorithm (for details see Augenstein, 2025). Our analyses focuses on extreme events, using the 90th percentile of convective clusters based on lightning stroke counts. Large-scale atmospheric flow patterns are classified by seven weather regimes from constant EOF pattern throughout the year (+ one undefined class) over the North Atlantic and European sector (80°W–40°E, 30°–90°N), with a temporal resolution of 6 hours, following the approach of Grams et al. (2017), adapted to ERA5 reanalysis by Hauser et al. (2023).

Table 1: Characteristics of the selected catchments.

Name of Catchment	State	Area (km ²)	Annual rainfall (mm/year)	Land Cover (dominant)	Population (2020)
Ahr Catchment	Rhineland-Palatinate / North Rhine-Westphalia	748	900	tree cover up to 367km ²	53,000
Erft Catchment	as above	1615	718	build-up up to 706 km ²	492,200
Danube Catchment	Bavaria and Baden-Württemberg	56,000	1020	agricultural 26976 km ²	9.7 million
Elbe Catchment	Eastern and Central Germany	96,932	659	agricultural up to 89230 km ²	18.5 million

RESULTS (A): EXTREME PRECIPITATION SCENARIOS

The spatial distribution of the 100 highest precipitation events from the observed data and the counterfactual scenarios with a shifting radius of 20 km is shown in Figure 1 (top panel). A notable increase in the intensity of extreme events can be seen throughout in the study area, but is most pronounced in the central and north-eastern parts. To understand the impact of such scenarios on flood risk, we calculated designed rainfall intensities for the whole of Germany and for specific catchments for different return periods. At each grid point, a Gumbel distribution is fitted to the top 100 events. The parameters obtained from the distribution are then used to estimate the designed rainfall intensity corresponding to the desired return periods (see Figure 1, bottom and Figure 2 for a 50-year return period).

For all counterfactual scenarios, a multi-fold increase in the designed rainfall intensity compared to the observed events is observed over most of Germany. There is also a large spatial variability in the distribution of high intensity over the north-eastern region, corresponding to the localized distribution of events (see Figure 1, bottom). Furthermore, the spatial distribution of the designed rainfall intensity over the selected catchments also

shows an anomalous and widespread increase in rainfall intensity and spatial variability, especially over the Ahr and Erft catchments (see Figure 2). However, more localized high-intensity events can be observed over the Danube and Elbe catchments. The increase in rainfall intensity for the counterfactual scenarios indicates a potential increase in flood risk.

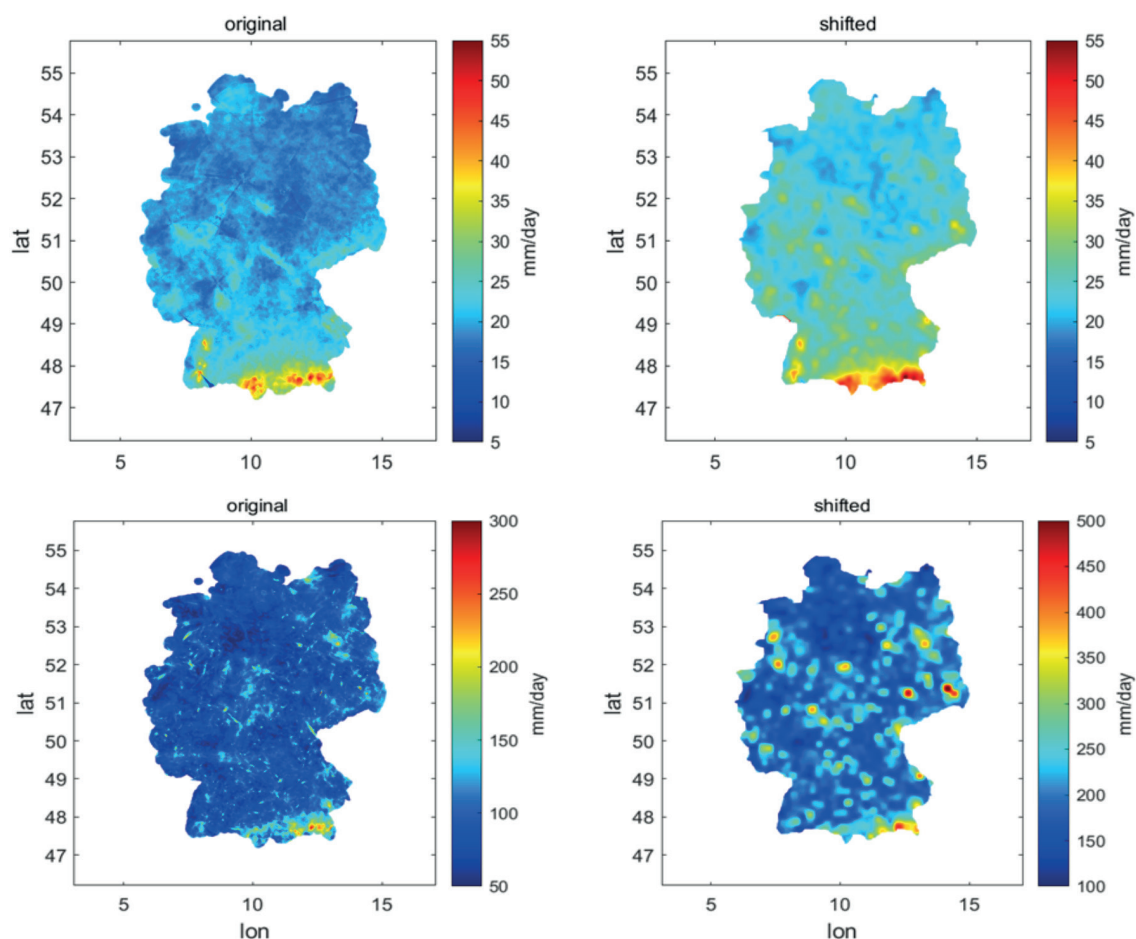
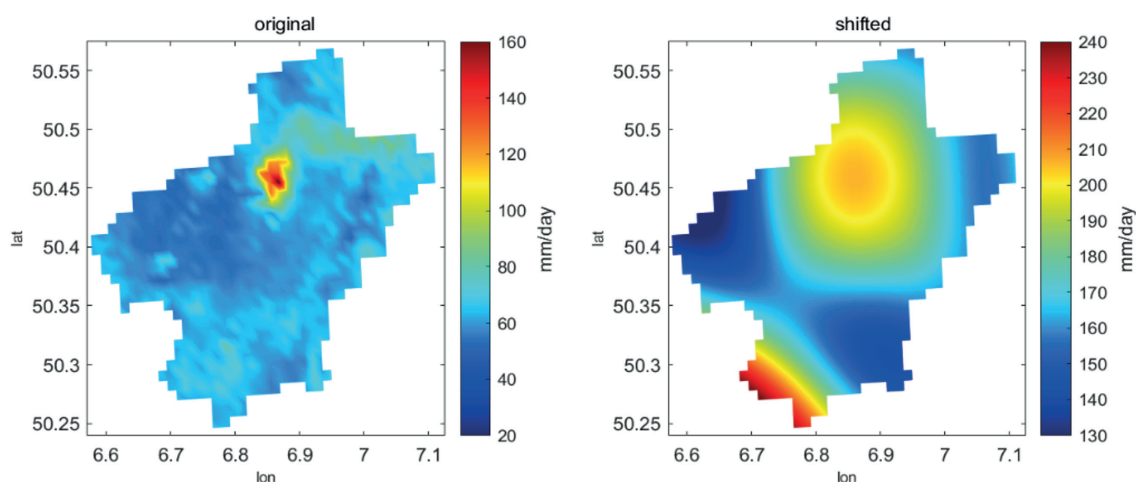


Figure 1: Top: Observed 100 highest rainfall events (left panel) and counterfactual scenario with 20 km² shift (right) over the Germany. Bottom: Designed rainfall for 50-yr return period for Germany for observed and shifted events.



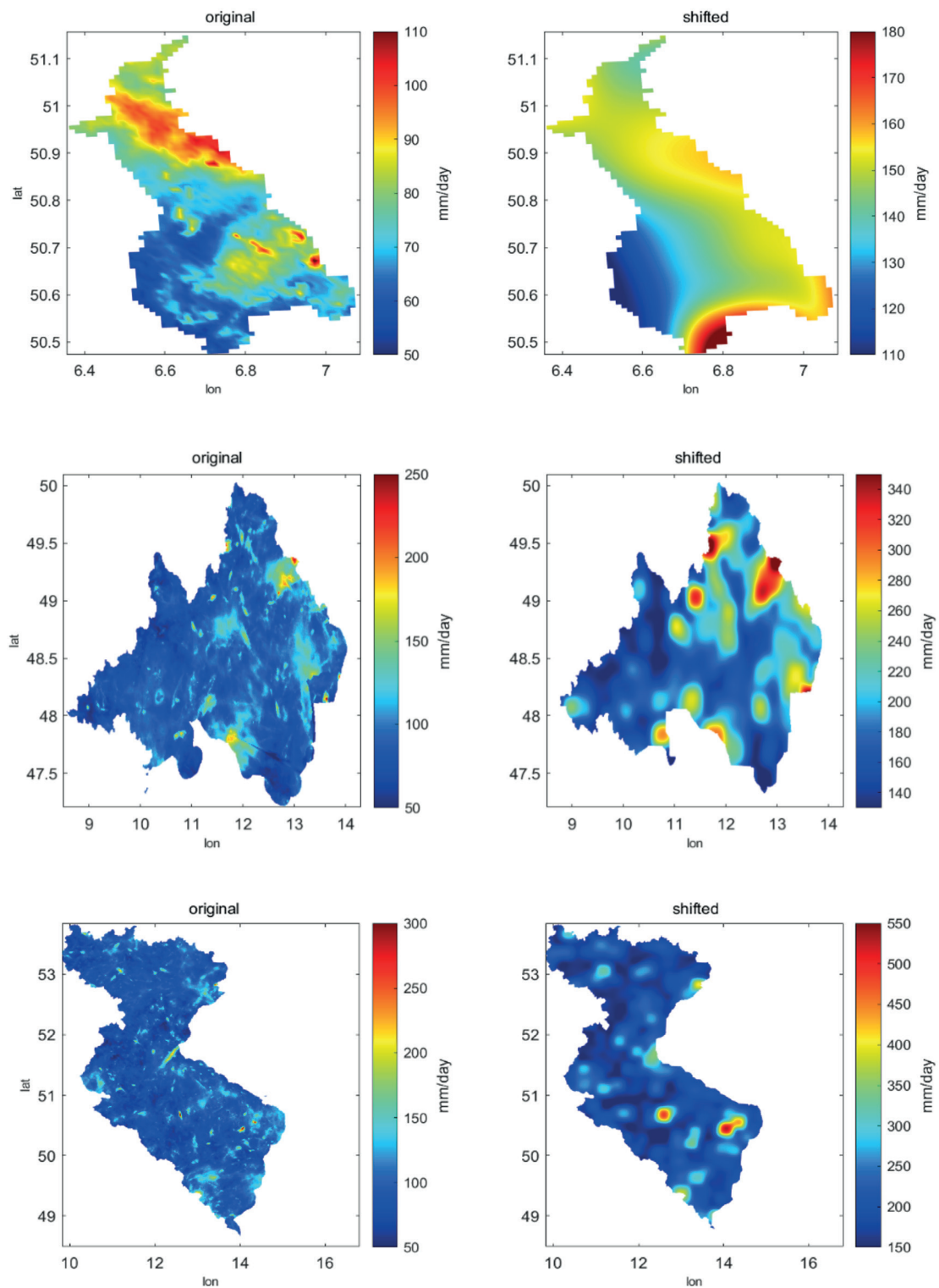


Figure 2: Designed rainfall for 50-yr return period observed (left) and shifted (right) for four catchments. From top to bottom: Ahr, Erft, Danube and Elbe.

RESULTS (B): WEATHER REGIMES

Of all weather regimes, the Scandinavian Blocking (ScBL) show the highest probability of occurrence for severe convective clusters in the extended study region and period (90% percentile, May to August). For example, positive values of YulesQ (Odds Ratio normalized to the interval $[-1,1]$), indicating increased convective activity during that regime, are found more or less for the entire study region (see Figure 3). About 2/3 of all grid points in Germany show significant positive values. The temporal analysis also shows that the ScBL regime are most frequent in July and August (not shown), when flash floods occur most frequently according to insurance data (Küpfer et al., 2025).

The number of convective clustered events significantly vary from one year to another with a slight tendency to a reduction in the probability for most of the patterns (see Figure 4). According to the analysis, most of the convective clustered events can be related to the ScBL regime, followed by the Greenland blocking (GL) regime. This finding applies to both the relative number of convective clustered events per year as well as to the number of grid points over the investigation area (see Figure 3). In contrast, the regimes of ZO, ScTR, and AR are least important for the occurrence of severe convective cluster events. Overall, the annual variability in the occurrence probability of the individual weather regimes is one important driver for the large annual variability of heavy rainfall potentially leading to severe flooding in small-to-medium sized catchments. Significant trends in the occurrence probability of the individual weather regimes cannot be identify, mainly because of the large annual variability. Also future climate scenarios do not show a large shift in the occurrence probability of the individual regimes, although the CESM-LE RCP8.5 ensemble run show a tendency towards a slightly positive change signal (not shown).

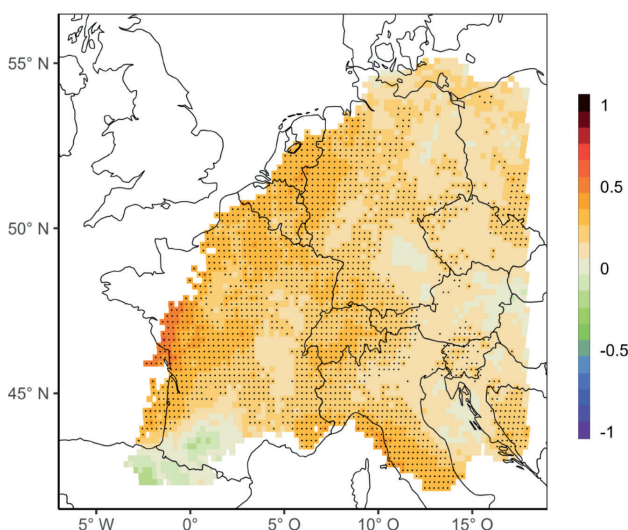


Figure 3: YulesQ for convective clusters during ScBL (2001-2021). Grid points with an average of less than two convective clusters per year are excluded from the calculation of YulesQ.

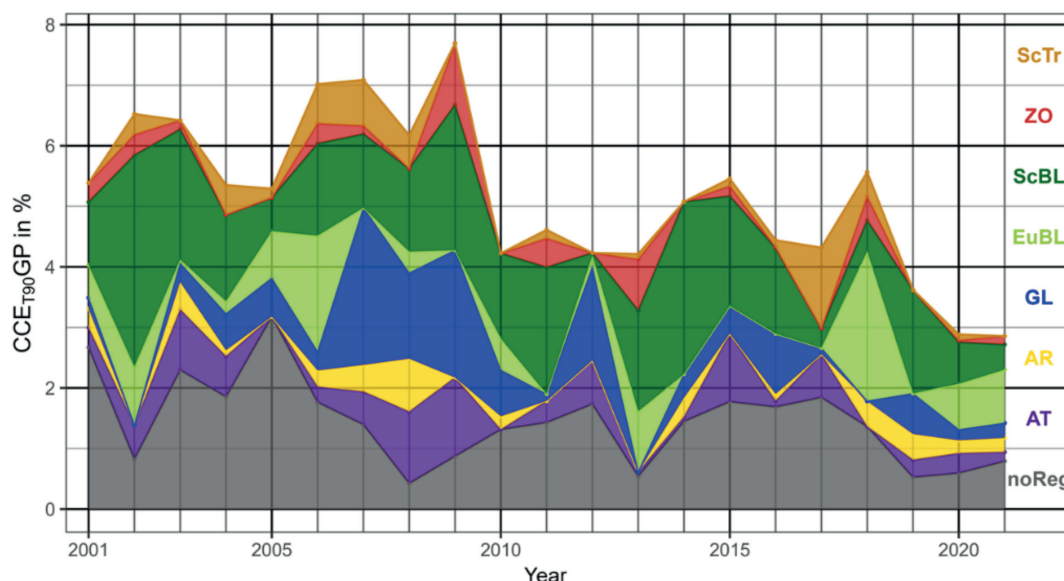


Figure 4: Number of grid points affected by a thunderstorm cluster (90th percentile = CCET90GP) per weather regime and year in relation to the total number of grid points (ScTr, AT = Scandinavian, Atlantic trough; ZO = zonal regime; ScBL, EuBL, GL = Scandinavian, European, Greenland Blocking; AR = Atlantic Ridge, noReg = unclassified). The different colors indicate the different weather regimes. Note that the maxima in the respective years indicate the percentage of thunderstorm clusters in relation to the total number of grid points.

CONCLUSIONS

This study has applied a counterfactual analysis by shifting observed extreme precipitation events in space to identify the potential impact on extreme precipitation events and has investigated the relation between convective clusters and large-scale weather patterns.

The shifting was performed across different spatial scales over Germany and selected catchments to investigate how relocating such events influences the magnitude and severity of extreme rainfall and floods. The analysis reveals a significant increase in rainfall intensity following the spatial shifting of observed extremes events. Our findings highlight the significance of counterfactual scenarios in enhancing flood forecasting systems and informing resilience planning for small to medium-sized catchments over Germany. Furthermore, these scenarios may be beneficial in constructing plausible storyline scenarios of future extreme events under changing climatic and hydrological conditions.

The statistical analysis of weather regimes and convective clusters revealed a dominant influence of the Scandinavian blocking regime on convective activity. This pattern, which peaks in July and August, exhibits substantial year-to-year variability, which can partly explain the pronounced temporal variability in precipitation and flood extremes. However, significant long-term trends cannot be detected in the time series over the past two decades.

Data Availability

The precipitation scenarios as well as lightning clusters and weather regime data are available via KIT.

Literature

- Augenstein, M., 2025. Variabilität, Trends und serielles Clustering schwerer Gewitterereignisse im Bezug zu großräumigen atmosphärischen Bedingungen. PhD thesis, Karlsruhe Institute of Technology (KIT), <https://doi.org/10.5445/IR/1000179408>
- Fang, B., Bevacqua, E., Rakovec, O. and Zscheischler, J., 2024. An increase in the spatial extent of European floods over the last 70 years. *Hydrology and Earth System Sciences*, 28(16), pp.3755–3775, <https://doi.org/10.5194/hess-28-3755-2024>
- Grams, C. M., Beerli, R., Pfenninger, S., Staffell, I., and Wernli, H., 2017. Balancing Europe's wind-power output through spatial deployment informed by weather regimes, *Nat. Clim. Change*, 7, 557–562, <https://doi.org/10.1038/nclimate3338>
- Hauser, S., Teubler, F., Riemer, M., Knippertz, P. und Grams, C. M., 2023. Towards a holistic understanding of blocked regime dynamics through a combination of complementary diagnostic perspectives. *Weather Clim. Dyn.* 4(2):399–425, <https://doi.org/10.5194/wcd-4-399-2023>
- Küpfer, K., Tuel, A. and Kunz, M., 2025. Impact-based temporal clustering of multiple meteorological hazard types in southwestern Germany. Preprints EGU sphere, <https://doi.org/10.5194/egusphere-2024-2803>
- Ludwig, P., Ehmele, F., Franca, M.J., Mohr, S., Caldas-Alvarez, A., Daniell, J.E., Ehret, U., Feldmann, H., Hundhausen, M., Knippertz, P. and Küpfer, K., 2023. A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe–Part 2: Historical context and relation to climate change. *Natural Hazards and Earth System Sciences*, 23(4), pp.1287–1311, <https://doi.org/10.5194/nhess-23-1287-2023>
- Merz, B., Nguyen, V.D., Guse, B., Han, L., Guan, X., Rakovec, O., Samaniego, L., Ahrens, B. and Vorogushyn, S., 2024. Spatial counterfactuals to explore disastrous flooding. *Environmental Research Letters*, 19(4), p.044022, <https://doi.org/10.1088/1748-9326/ad22b9>
- Mohr, S., Wandel, J., Lenggenhager, S. and Martius, O., 2019. Relationship between atmospheric blocking and warm-season thunderstorms over western and central Europe. *Quarterly Journal of the Royal Meteorological Society*, 145(724), pp.3040–3056, <https://doi.org/10.1002/qj.3603>
- Mohr, S., Ehret, U., Kunz, M., Ludwig, P., Caldas-Alvarez, A., Daniell, J.E., Ehmele, F., Feldmann, H., Franca, M.J., Gattke, C. and Hundhausen, M., 2022. A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe. Part 1: Event description and analysis. *Natural Hazards and Earth System Sciences Discussions*, 2022, pp.1–44, <https://doi.org/10.5194/nhess-23-525-2023>
- Montanari, A., Merz, B. and Blöschl, G., 2023. HESS Opinions: The Sword of Damocles of the Impossible Flood. *EGU sphere*, 2023, pp.1–20, <http://dx.doi.org/10.5194/nhess-2023-224>
- Tarasova, L., Lun, D., Merz, R., Blöschl, G., Basso, S., Bertola, M., Miniussi, A., Rakovec, O., Samaniego, L., Thober, S. and Kumar, R., 2023. Shifts in flood generation processes exacerbate regional flood anomalies in Europe. *Communications Earth & Environment*, 4(1), p.49, <https://doi.org/10.1038/s43247-023-00714-8>
- Winterrath, T., Brendel, T., Junghänel, T., Klameth, A., Lengfeld, K., Walawender, E., Weigl, E., Hafer, M. and Becker, A., 2019. An overview of the new radar-based precipitation climatology of the Deutscher Wetterdienst–data, methods, products. In *Rainfall Monitoring, Modelling and Forecasting in Urban Environment. UrbanRain18: 11th International Workshop on Precipitation in Urban Areas. Conference Proceedings* (pp. 132–137). ETH Zurich, Institute of Environmental Engineering, <https://doi.org/10.3929/ethz-b-000347607>

Future scenarios through jet stream nudging

Authors: John, A.¹, Beyer, S.¹, Goessling, H.F.¹, Sanchez-Benitez, A.¹, Athanase, M.¹, Jung, T.^{1,2}

Affiliation(s): ¹ Alfred Wegener Institute Helmholtz-Center for Polar and Marine Research, Bremerhaven,

² University of Bremen, Institute of Environmental Physics, Bremen.

Email (Corresponding Author): thomas.jung@awi.de

INTRODUCTION

As global warming intensifies, the demand for precise, actionable climate information grows, especially to understand and prepare for extreme weather events. Traditional climate models, while foundational, often lack the spatial resolution and event-based framing needed for local decision-making. This study addresses this gap by combining kilometre-scale (km-scale) global climate modelling with spectral nudging to develop physically consistent, high-resolution climate storylines.

Spectral nudging constrains large-scale atmospheric patterns to observations while allowing small-scale dynamics to evolve freely (Sánchez-Benítez et al., 2021). When applied in coupled atmosphere-ocean models at km-scale resolution (≤ 10 km), this method enables the realistic simulation of localised weather phenomena like convective storms and heavy precipitation. Such fidelity is essential for capturing the nuanced impacts of climate change. The storyline approach – a framework for exploring “what-if” climate scenarios – has emerged as a powerful tool for risk assessment and adaptation planning. It allows us to examine how specific events, such as heatwaves or marine heatwaves, might evolve under different climate states (pre-industrial, present-day, or future). While past studies have mainly relied on coarse-resolution models, this report explores the added value of integrating km-scale models to enhance spatial detail and physical realism.

Compared to regional approaches such as dynamical downscaling or Pseudo Global Warming (PGW), our km-scale global framework avoids limitations related to boundary conditions, sea ice inconsistencies, and missing teleconnections. It ensures global physical consistency and allows smooth transitions between regions of interest – an important advantage when studying extreme events and their drivers.

Recent advances in high-performance computing make global km-scale simulations feasible. Building on these developments, this report – conducted in collaboration with the European Union’s Destination Earth (DestinE) initiative – presents km-scale nudged simulations across multiple climate states. The report demonstrates how this approach can provide detailed, physically consistent storylines that support adaptation strategies and improve our understanding of future risks. This report is a short version of a preprint (John et al., 2024).

METHODS

This study uses a novel global km-scale climate modelling framework based on the coupled model IFS-FESOM (Rackow et al., 2025), which integrates ECMWF's Integrated Forecasting System (IFS) with the ocean and sea-ice model FESOM2. The setup features high horizontal (≈ 9 km) and vertical resolution, using unstructured ocean grids that support eddy-rich simulations in key ocean regions.

Spectral nudging is applied to the vorticity and divergence fields in the middle and upper troposphere, constraining large-scale atmospheric circulation (and the jet stream in particular) to ERA5 reanalysis data (Hersbach et al. 2020) while allowing small-scale and thermodynamic processes to evolve freely. The method ensures realistic weather evolution, particularly in the extratropics, while preserving the model's capacity to simulate local extremes.

Three climate scenarios were simulated:

- Control (Cont) for pre-industrial (~ 1950),
- Historical (Hist) for present-day conditions (2017–2024), and
- Tp2K for a +2K warmer future (≈ 2040)

with tailored initializations and forcings from CMIP6 and NextGEMS. Despite some limitations in spin-up length and consistency across experiments, the design captures fast climate processes relevant for extreme event analysis.

Simulations were run on the LUMI pre-exascale supercomputer, achieving ~ 600 simulated days per day with high temporal output resolution (~ 100 GB/day). The setup allows both detailed reconstruction of observed events and the generation of physically consistent storylines for different climate states, forming the backbone of the report's later analyses.

RESULTS

Extreme Event Depictions: Heatwave and Storm Boris

The July 2019 European heatwave and the September 2024 Storm Boris event offer two compelling examples of how the kilometre-scale nudged simulations enhance our ability to capture and understand extreme weather. Both events were simulated using the km-scale IFS-FESOM model and compared with a coarser-resolution configuration (AWI-CM1) nudged to the same large-scale conditions (see Figure 1).

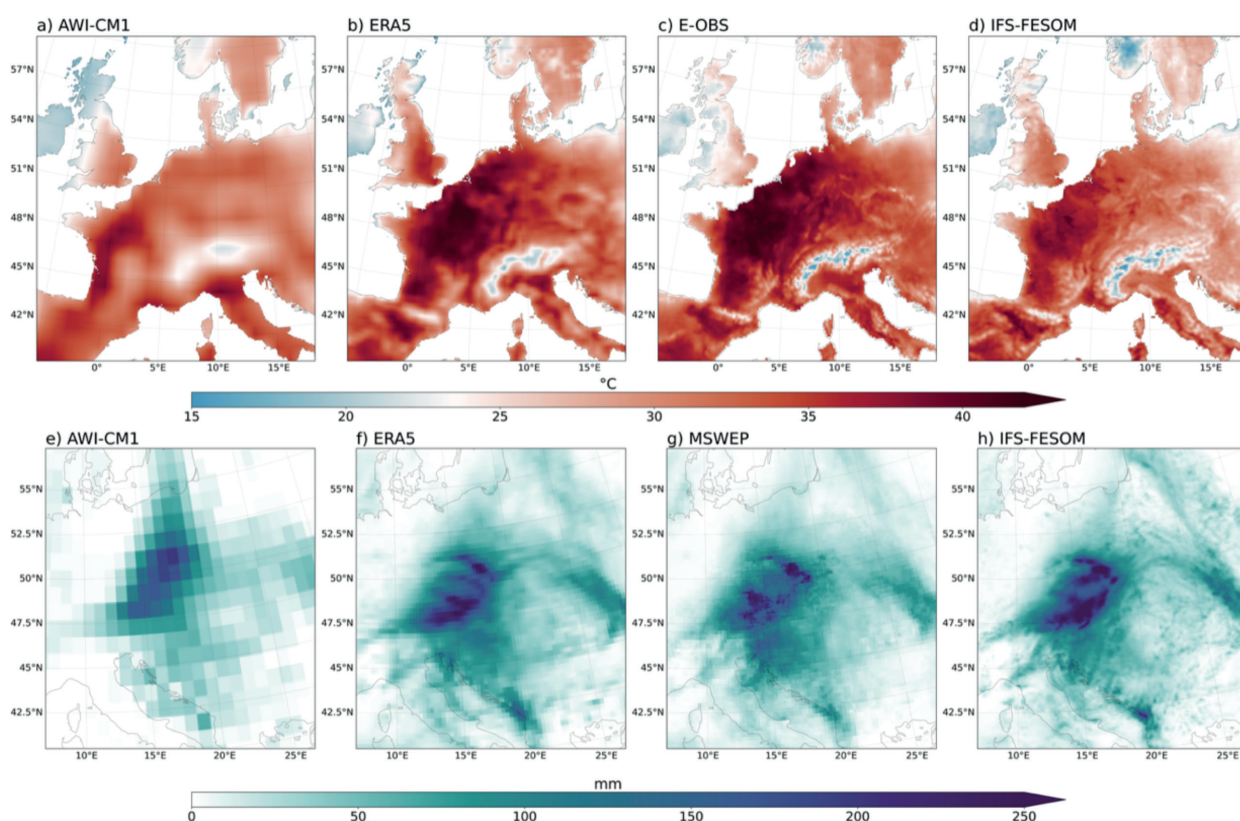


Figure 1: Comparison of extreme weather events simulated with the km-scale nudged IFS-FESOM model and the coarser-resolution AWI-CM1 model, evaluated against observational and reanalysis datasets. The top panels (a–d) show the maximum 2-metre temperature during the peak of the July 25, 2019, European heatwave. The bottom panels (e–h) present the 5-day accumulated precipitation during Storm Boris (September 12–16, 2024). The IFS-FESOM simulations show improved alignment with ERA5, E-OBS, and MSWEP datasets, highlighting the added value of km-scale resolution for accurately capturing the intensity and spatial structure of extreme events.

For the heatwave, the km-scale model provides a much more detailed representation of local temperature extremes, particularly in regions with complex terrain and urban structures. Notably, the model captures elevated temperatures over Paris, consistent with the observed record of 42.6°C, and reveals spatial patterns shaped by topography and land surface heterogeneity. This level of granularity is crucial for understanding and preparing for the impacts of heat extremes, especially in urban areas where the interplay between surface characteristics and atmospheric conditions can amplify local heat stress.

The same km-scale setup also improves the simulation of Storm Boris, a heavy precipitation event that affected parts of Europe in mid-September 2024. While the coarser AWI-CM1 model outlines the general area of

rainfall, the km-scale simulation resolves more realistic spatial structures, including narrow rain bands and sharp gradients that are typical of convective systems. Such detail is essential for assessing localized flood risk and for understanding how extreme precipitation events may intensify in a warmer climate.

Climate Change Storylines for Storm Boris

The Boris storm event is further examined by comparing cumulative rainfall and hourly precipitation evolution under three climate states: pre-industrial (Cont), present-day (Hist), and a +2K warmer world (Tp2K) (see Figure 2). Each scenario is represented by an ensemble of five km-scale nudged simulations, which helps isolate the climate signal from internal variability while retaining local detail.

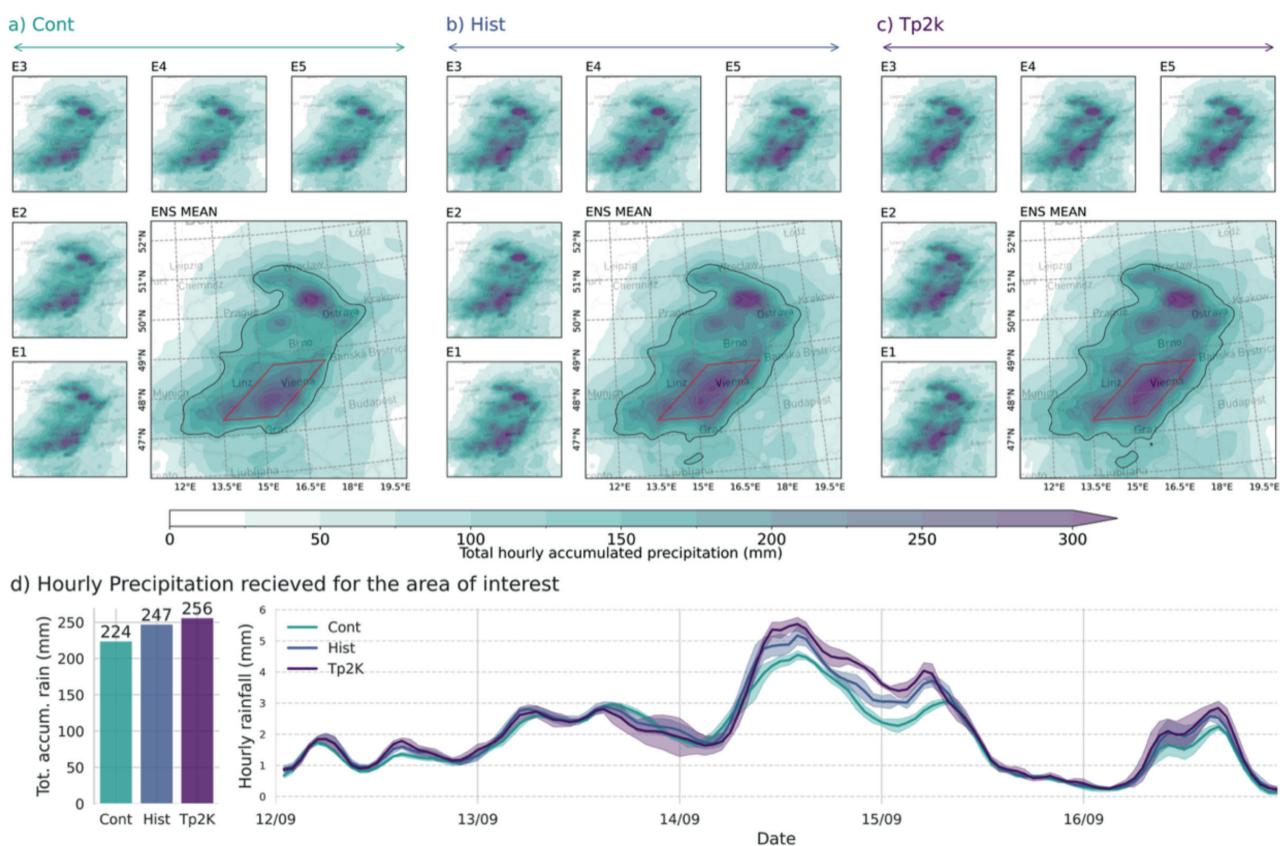


Figure 2: Total cumulative precipitation associated with Storm Boris (September 12–16, 2024) as simulated by the three storyline experiments: pre-industrial (Cont), present-day (Hist), and a +2K future climate (Tp2K). The top panels show individual ensemble members (E1–E5) and the corresponding ensemble mean (“ENS MEAN”) for each experiment. Black contour lines indicate areas where cumulative rainfall exceeds 120 mm. The bottom charts display total event precipitation (bars) and the evolution of hourly rainfall (lines) within the red polygonal region shown in the maps. This comparison illustrates how the same weather situation might have unfolded under different climate conditions. The high-resolution IFS-FESOM simulations provide detailed spatial and temporal insights into changes in rainfall intensity and distribution across climate scenarios.

The results reveal a clear intensification and spatial expansion of heavy rainfall with warming. The area experiencing more than 120 mm of precipitation increases by 19% from Cont to Hist, and by a further 8% from Hist to Tp2K. Although the total accumulated rainfall increases modestly from Hist to Tp2K (+3.6%), the peak hourly

rainfall rates are significantly higher, and the timing of peak precipitation shifts. These changes are especially relevant for flood forecasting and emergency planning, as higher peak intensities and altered event timing can greatly affect local impacts.

This case study illustrates how km-scale climate storylines can capture both thermodynamic intensification and fine-scale structural changes in precipitation. It highlights the importance of high-resolution modelling for quantifying the evolving risks of extreme events under climate change and offers a powerful tool for supporting targeted adaptation strategies.

CONCLUSIONS

This study introduces a new global modelling framework that combines kilometre-scale (km-scale) resolution with spectral nudging to generate high-fidelity storylines of extreme weather events under different climate conditions. By constraining large-scale atmospheric circulation to observations while resolving fine-scale processes, the approach delivers physically consistent simulations that align well with both reanalysis data and high-resolution observations, including those from the MOSAiC campaign.

The use of the IFS-FESOM model at km-scale resolution enables a more realistic representation of extreme events, especially in complex terrains and coastal or urban regions. Compared to conventional coarse-resolution models, this approach significantly improves the simulation of temperature and precipitation extremes, providing more actionable insights for adaptation and risk assessment. High computational efficiency achieved on Europe's LUMI supercomputer makes such simulations increasingly feasible.

This work builds on developments initiated in the HICAM and HICAM2 projects and will be continued and made operational as part of the Climate Digital Twin (Climate DT) of the European Union's Destination Earth initiative. As a next step, expanding the ensemble size, refining sea-ice representation, and extending the storyline approach to higher warming levels (e.g., +3K, +4K) will further enhance the utility of this framework. Together, these efforts aim to deliver tangible, localised climate information that connects global change to local impacts in support of science, policy, and preparedness.

A near-real-time storyline system based on a CMIP6-class model has already been developed within the SCENIC Innovation Pool project (Athanas, Sanchez-Benitez et al., 2024). This system, which is available here: <https://climate-storylines.awi.de>, demonstrates the potential to provide timely, event-based climate storylines in response to emerging extreme events. Building on this experience, similar near-real-time capabilities will be implemented for the km-scale system later in 2025 in the context of Destination Earth, enabling a new generation of high-resolution, on-demand climate storylines to support impact assessments and early response strategies.

DATA AVAILABILITY

The data from the nudging experiments are available through the DestinE Platform: <https://platform.destine.eu>.

Literature

- Athanase, M., A. Sanchez-Benitez, E. Montfort, T. Jung, and H.F. Goessling, 2024: How climate change intensified storm Boris' extreme rainfall, revealed by near-real-time storylines. *Commun. Earth Environ.*, 5, 676 (2024).
<https://doi.org/10.1038/s43247-024-01847-0>.
- Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>
- Amal J., and Coauthors, 2024. Global storyline simulations at the kilometre-scale. ESS Open Archive .
November 14, 2024. DOI: [10.22541/essoar.173160166.64258929/v1](https://doi.org/10.22541/essoar.173160166.64258929/v1)
- Rackow, T., and Coauthors, 2025: Multi-year simulations at kilometre scale with the Integrated Forecasting System coupled to FESOM2.5/NEMOv3.4. *Geosci. Model Dev.*, 18, 33–69, <https://doi.org/10.5194/gmd-18-33-2025>.
- Sánchez-Benítez A., H. Goessling, F. Pithan, T. Semmler, and T. Jung, 2021: The July 2019 European heatwave in a warmer climate: Storyline scenarios with a coupled model using spectral nudging. *Journal of Climate*. 35, 2372–2390, <https://doi.org/10.1175/JCLI-D-21-0573.1>

Toward a High-resolution Flash Flood Impact-based Forecasting in Germany – Proof of Concept

Authors: Najafi, H.¹, Mohannazadeh, M.¹, Shrestha, P.¹, Nithila Devi, N.², Weiß, T.³, Vorogushyn, S.², Apel, H.², Attinger, S.¹, Merz, B.², Samaniego, L.¹

Affiliation(s): ¹ Helmholtz-Centre for Environmental Research (UFZ), Leipzig, ² Helmholtz Centre for Geosciences, Section 4.4 Hydrology, Potsdam, ³ Helmholtz Centre for Geosciences, Section 5.2 eScience Centre

SUMMARY

Extreme precipitation and flash floods are increasingly threatening communities, highlighting the urgent need for more advanced early warning systems delivering actionable information. This project aims to develop an experimental, impact-based flood forecasting and early warning system in selected German basins, to test its feasibility and merits. The prototype operational system should provide high-resolution spatial and temporal forecasts of flash floods and their impacts. It integrates operational weather forecast products with hydrologic and inundation models to improve disaster preparedness and response.

The shift toward impact-based early warning systems is gaining global momentum, as national hydro-meteorological services increasingly prioritize this approach (Merz et al., 2020, Golding, 2022). Also, World Meteorological Organization (WMO) advocates for transitioning from traditional weather forecasts to impact-based forecasting and warning services (WMO, 2015; 2018).

Following the devastating summer flood of 2021 in western Germany, researchers at UFZ and GFZ initiated the development of a high-resolution, experimental impact-based flood forecasting and early warning system (FFEWS). The forecasting chain is built upon in-house hydrologic and hydrodynamic models, **mHM** and **RIM2D**. A key advantage of the proposed system is its ability to cover the entire forecasting chain – from triggering meteorological events to flood inundation and impact prediction – in quasi-real-time, with run times significantly shorter than forecast horizon. It also propagates uncertainties originating from atmospheric initial conditions and through the model chain. In comparison to static flood hazard maps, the probabilistic flood inundation and impact forecasts deliver more specific and actionable information. The proof of concept for this forecasting approach was recently published and has received recognition from both the scientific community and media outlets¹ (see Najafi et al., 2024).

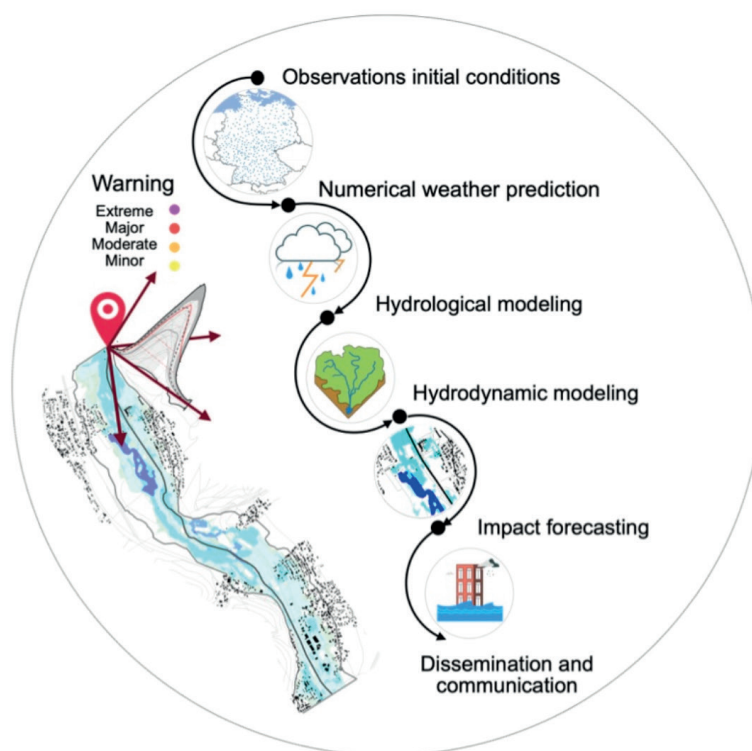
Finally, we started the integration and testing SINFONY weather forecast products with the developed FFEWS. SINFONY is an experimental pilot project by the German Weather Service (DWD) that combines nowcasting with a rapid update cycle (RUC) numerical weather predictions. Incorporating SINFONY data is expected to significantly improve the prediction accuracy for flood events driven by convective storms.

Impact-based flood forecasting and early warning system

The prototype impact-based flood forecasting and early warning system (FFEWS) is developed in cooperation between UFZ and GFZ. It utilizes weather forecast products operationally delivered by ECMWF and DWD to drive hydrological, hydrodynamic and flood impact predictions. Figure 1 illustrates the main components of the proposed impact-based FFEWS. The system integrates components with varying spatial resolutions and

¹ As of March 2025, when this report was written, it has been downloaded over 13,000 times.

technology readiness levels (TRLs). Numerical weather prediction operates at 1 and 4 km resolution, while hydrological and hydrodynamic modeling achieve much finer resolutions, down to 1-10 m. Additionally, the number ensemble members used across the forecasting chain ranges from 10 to 51, depending of the component. The initialization sequence is described in Samaniego et al. (2019).



Model/characteristic	Daily updates	Technology readiness level	Spatial Resolution	Ensemble member
Numerical weather prediction	1 - 8	7 - 9	1 - 4 km	10 - 51
Hydrological forecasting	1 - 8	7 - 9	100 m - 5 km	10 - 51
Hydrodynamic modeling and impact forecasting	Triggered upon reaching flood discharge thresholds	7 - 9	1 - 10 m	5

Figure 1: Schematic of the proposed impact-based flood forecasting and early warning system (FFEWS), showing key components along with their update frequencies, spatial resolution, and technology readiness levels (TRLs) (after Najafi et al., 2024).

Table 1: Datasets used for deriving observational-based initial conditions, model set-up, and calibration of the hydrologic and hydrodynamic FFEWS components shown in Figure 1.

Input data	Source	Dataset/variables	Temporal Resolution	Details
Meteorological	DWD	Precipitation (station, RADOLAN-RW, HYRAS), average temperature (station), maximum and minimum air temperature (station)	Hourly and daily	retrieved from DWD portal
Catchment characteristics	BGR, BKG	Soil map, land use map, digital elevation model (DEM)	static	see Boeing et al. (2023)
Hydrological	GRDC	Discharge observations at river gauges	Hourly and daily	
Floodplain and inundation characteristics	BKG, other sources	10-m digital elevation model (DEM), land use map, flood marks, inundation extent of past floods	static	see Apel et al. (2022)
Exposure	Open Street Map (OSM)	Location data of buildings, roads and railways	static	

UFZ is retrieving short- and medium-range ensemble weather forecasts in real time from both the German Weather Service (DWD) and the European Centre for Medium-Range Weather Forecasts (ECMWF). This multi-model approach provides a comprehensive representation of uncertainties associated with prediction of key weather variables. This provides a foundation for further research on ensemble-based flood impact forecasting. Table 2 provides detailed information on the weather forecast products from various sources used in this study.

We developed interfaces to deploy ensemble forecasts from the numerical weather prediction (NWP) models ICON-D2-EPS and IFS operated by DWD and ECMWF, respectively. Furthermore, we started an integration of experimental SINFONY data including the Rapid Update Cycle (RUC) and INTENSE products (see Table 2). The RUC data result from the NWP with a more frequent update frequency and shorter forecast horizons compared to the standard ICON-D2-EPS ensemble. Finally, the INTENSE product combines the operational NWP with now-casting data to deliver seamless short-term precipitation forecasts up to +12 hours ahead. It is updated every 5 minutes and is expected to be particularly suitable for forecasting rapidly evolving, convective precipitation events.

Table 2: Characters of atmospheric forecasts retrieved for real-time flood forecasting in HI-CAM II.

Centre	NWP/model	Ensemble member	Update frequency	Temporal Resolution (min)	Forecast Horizon (hr)	Spatial Resolution
DWD	ICON-D2-EPS	20	Every 3 hour	15	48	~ 2.2 km
	SINFONY (ICON-RUC-EPS)	21	Every half an hour	15	14	
	SINFONY INTENSE	21	Every 5-min		12	
ECMWF	IFS	51	Every 6 hour	60	72	~ 9km

mHM

The mHM hydrologic model is based on numerical approximations of dominant hydrological processes. In general, this model simulates the following processes: canopy interception, snow accumulation and melting, soil moisture dynamics, infiltration and surface runoff, evapotranspiration, subsurface storage and discharge generation, deep percolation and baseflow, and discharge attenuation and flood routing. A distinctive feature of mHM is its Multiscale Parameter Regionalization (MPR) technique, which links model parameters defined at a coarse spatial scale (Level-1) to a finer resolution grid (Level-0) using spatial upscaling operators. This approach enables consistent parameterization across scales, enhancing the model's transferability and robustness. Further details on the model structure, implementation, and applications can be found in (Samaniego et al., 2010).

To generate hydrologic initial conditions for each river discharge forecast initialization, mHM should be driven by near-real-time gridded observational data (gridded average temperature and precipitation). However, the German weather service (DWD) does not currently provide gridded hourly temperature data in near-real-time. For precipitation, RADOLAN-RW (Radar-Adjusted Precipitation Data – Hourly) is available as near-real-time gridded product but it tends to underestimate precipitation (Demuth & Rademacher, 2016). An alternative approach involves bias-adjusting 24-hour RADOLAN-RW precipitation totals to match HYRAS (Hydrometeorologische Rasterdatensätze) daily data, followed by temporal disaggregation to produce hourly precipitation inputs (Najafi et al., 2024). However, this method is only feasible for forecast initialization at 06 UTC, once HYRAS data becomes available online, or for retrospective hindcast experiments. Since RADOLAN-RW is usually under-estimating precipitation, we estimated variograms of hourly precipitation and 2m hourly average temperature across Germany to interpolate DWD station data onto 1-km grid for hydrological modeling. For real-time applications, these high-resolution gridded fields were generated using Kriging with elevation as an external drift (EDK)² (Samaniego et al., 2011).

Cross-validation was employed to identify the optimal variogram type and interpolation method (Ordinary and External Drift Kriging (OK, EDK) and determine the most suitable special range. The performance of the inter-

² https://git.ufz.de/chs/progs/edk_nc/-/tree/edk_nc_hourly?ref_type=heads

polated dataset – particularly EDK with an exponential variogram – was validated for temperature against the HOSTRADA dataset from the period 1995-2023. The comparison yielded a root mean square error (RMSE) of 0.8 °C, demonstrating the robustness and accuracy of the approach.

To enable mHM for high-frequency flood forecasting (e.g., every hour), the model has been extended to read meteorological inputs and write sub-daily discharge outputs. From a technical standpoint, additional modifications have been implemented to allow mHM to run from any hour of the day and for periods that are not restricted to multiples of 24 hours (e.g., 3 or 6 hours).

RIM2D

RIM2D is a grid-based hydrodynamic model for the simulation of inundation dynamics in the floodplains delivering estimations of inundation depths, flooded areas and flow velocities. RIM2D solves the inertial formulation of the shallow water equations using an explicit numerical scheme including an adaptive time stepping mechanism (Bates et al., 2010), and numerical diffusion for additional numeric stability (Almeida et al., 2012). RIM2D is coded in FORTRAN90, with the hydraulic kernel coded in FORTRAN CUDA for massive parallelization on NVIDIA Graphic Processor Units (GPUs). In the HI-CAM phase I, RIM2D was developed to consider an urban setting, the sewer system and infiltration on non-sealed surfaces by applying a capacity-based approach for both the sewer system and infiltration (Apel et al., 2024). Meanwhile, RIM2D model is implemented on multiple GPUs within the Helmholtz Validation project and can be upscaled to GPU-based High-Performance Clusters. This significantly reduces simulation runtimes, making hydrodynamic modeling operationally feasible within real-time flood early warning systems. Apel et al. (2022) demonstrated the RIM2D performance in the retrospective analysis of the 2021 Ahr Valley flood. Thus, the RIM2D model can run on high-resolution terrain data while optimizing the tradeoff between computational efficiency and accuracy.

Flood Forecasting Workflow

Figure 2 presents the workflow diagram of the proposed operational forecasting chain. Numerical Weather Prediction (NWP) forecasts are stored on the UFZ High-Performance Computing (HPC) system, the EVE Cluster. The entire data processing pipeline – including meteorological input handling, hydrologic and hydrodynamic modeling, and post-processing – is executed operationally within a unified ecFlow workflow suite on EVE. To support this system, RIM2D has been installed and configured for GPU-based execution on the cluster. When a predefined flood threshold is exceeded – based on return period estimates – a triggering mechanism activates the flood inundation module. Inundation simulations are then run for selected ensemble percentiles using the available GPU resources, enabling timely and spatially detailed flood forecasts. Further, based on the simulated maximum inundation extents, impact indicator products such as lead time and exceedance probability maps will be simulated.

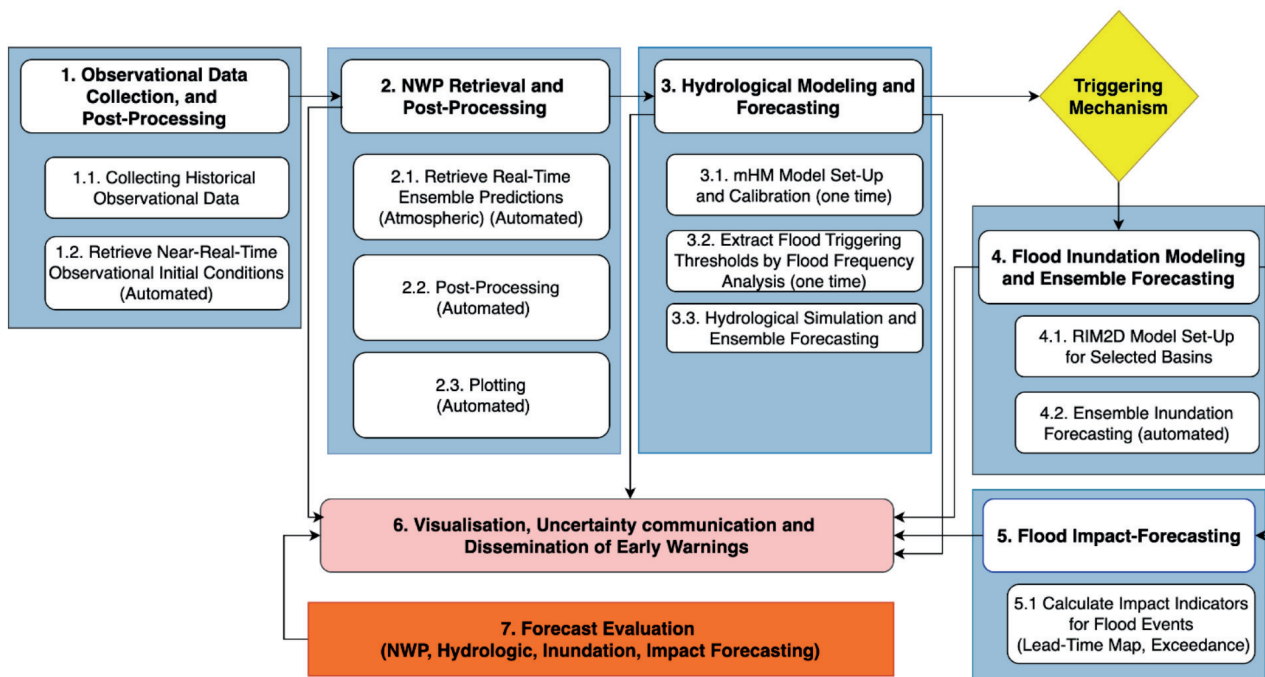


Figure 2: Workflow diagram of the flood forecasting chain.

Study Domain

The prototype FFEWS is setup and tested in the Ahr river basin for the July 2021 flood event and in the Fils catchment (Neckar tributary) for the flash flood event on June 2nd, 2024. An attempt to setup and test the FFEWS in the Murr catchment (Neckar tributary) for the recent flash flood in May 2024 was discarded due to difficulties in obtaining event data. The relatively small size of the Ahr and Fils catchments and their morphological features including narrow streams and steep slopes with shallow soils make them prone to flash floods. The mHM was setup for the Ahr and Fils catchments based on catchment characteristics provided in Table 1. For the Ahr catchment, the hydraulic domain spans between the towns of Altenahr and Sinzig. The domain consists of the larger urban area of Bad Neuenahr-Ahrweiler. For the Fils catchment, the hydraulic domain spans between the towns of Salach and Plochingen.

The RIM2D model was setup at 10 m and 5 m spatial resolution for the Ahr and Fils domains, respectively, resulting in 1.3 and 8.85 million computational cells. Discharge simulations from mHM are generated at interface points (gauge Altenahr in the Ahr catchment) and (gauge Salach in the Fils catchment). The DEM was obtained from the German Federal Agency for Cartography and Geodesy (BKG). The data sources for the other input data such as buildings and land use and land cover are OpenStreetMap and CORINE land use classification, respectively.

RESULTS

Uncertainty in quantitative precipitation estimation based on interpolated gauge data and gauge adjusted radar data

As previously noted, during the 2021 summer flood, RADOLAN-RW recorded precipitation values that were approximately 30% lower than the best estimate (LfU report, 2024). To further investigate these discrepancies, we compared hourly gauge data and RADOLAN-RW against daily HYRAS data as a reference (see Figure 3). The results show that RADOLAN-RW exhibits greater variability and frequently underestimates precipitation relative to HYRAS. In contrast, hourly gauge data, interpolated using estimated variograms demonstrate better agreement with HYRAS's daily totals, indicating improved consistency.

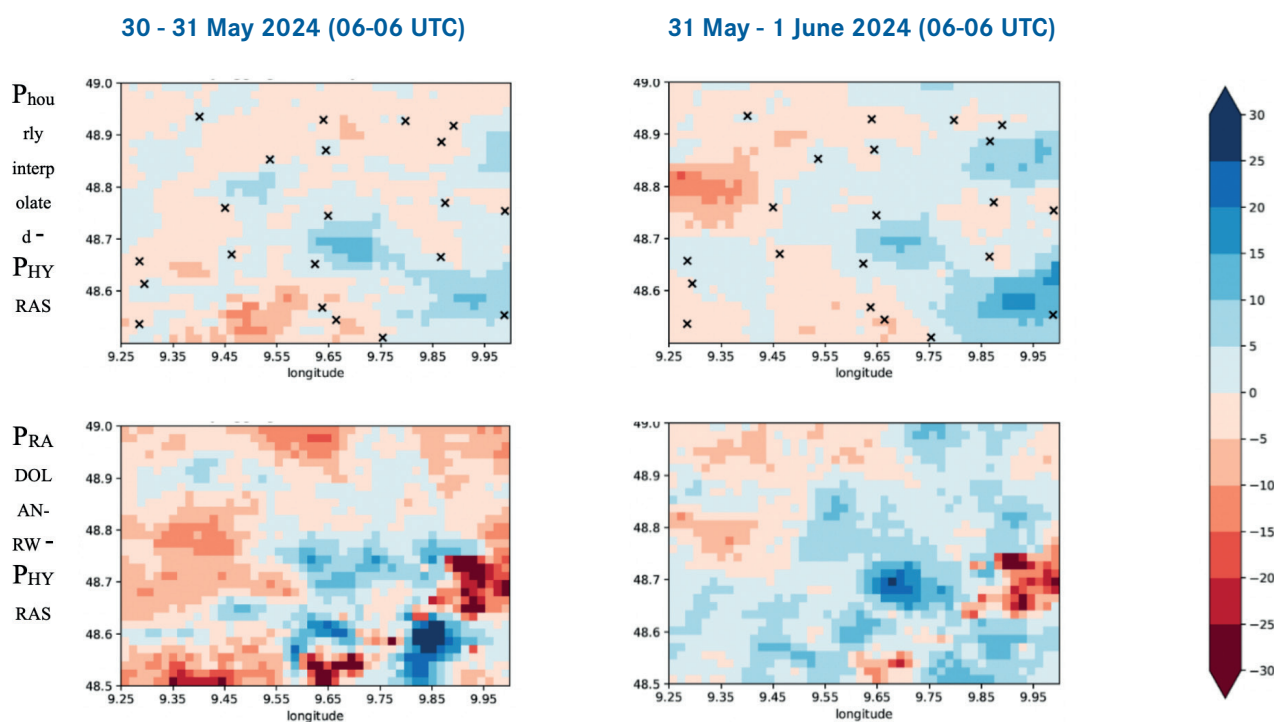


Figure 3: Comparison between 24-h sum of RADOLAN-RW and HYRAS (shown in left column) and total 24-h sum of interpolated hourly gauge data and HYRAS (shown in right column) for flooding event in May and June 2024 in Swabia.

In operational flood forecasting centers, multiple precipitation datasets are typically evaluated to generate hydrological initial conditions. The dataset that yields river discharge estimates closest to observed values is generally selected for forecast initialization. However, to enhance the reliability of hydrological initial conditions, it is essential to assess the uncertainties associated with different precipitation products over multiple events and extended time periods. This evaluation should consider factors such as rain gauge density, catchment size, and geographic location, which can significantly influence performance across various flood events.

Flood forecasting for the 2021 Ahr Valley flood and the 2024 Fils flood

Figure 4 presents ensemble forecasting results from two experiments conducted in this project, using ICON-D2-EPS and IFS. Figure 4a displays 320 ensemble water level predictions generated by the ICON-D2-EPS-mHM chain for the Ahr flood in July 2021. For each forecast initialization, the probability of exceeding HQ50 and HQ100 water level thresholds was computed. The hindcast experiment demonstrates that the probability of exceeding these thresholds surpassed 50%, with a lead time of up to 17 hours (Najafi et al., 2024). Although the ensemble forecasts did not fully reproduce the reconstructed flood peak, the probabilistic exceedance information still offered valuable guidance for early warning and decision-making. Figure 4b shows ensemble river discharge forecasts at the Salach gauge, generated using the IFS-mHM setup. This comparison illustrates the performance of different NWP systems in providing timely and probabilistic flood information across distinct catchments. The hydrographs from the IFS-mHM chain were used as boundary conditions for the RIM2D model in simulating the 2021 and 2024 floods of the Ahr and Fils catchments (see Figure 4), respectively.

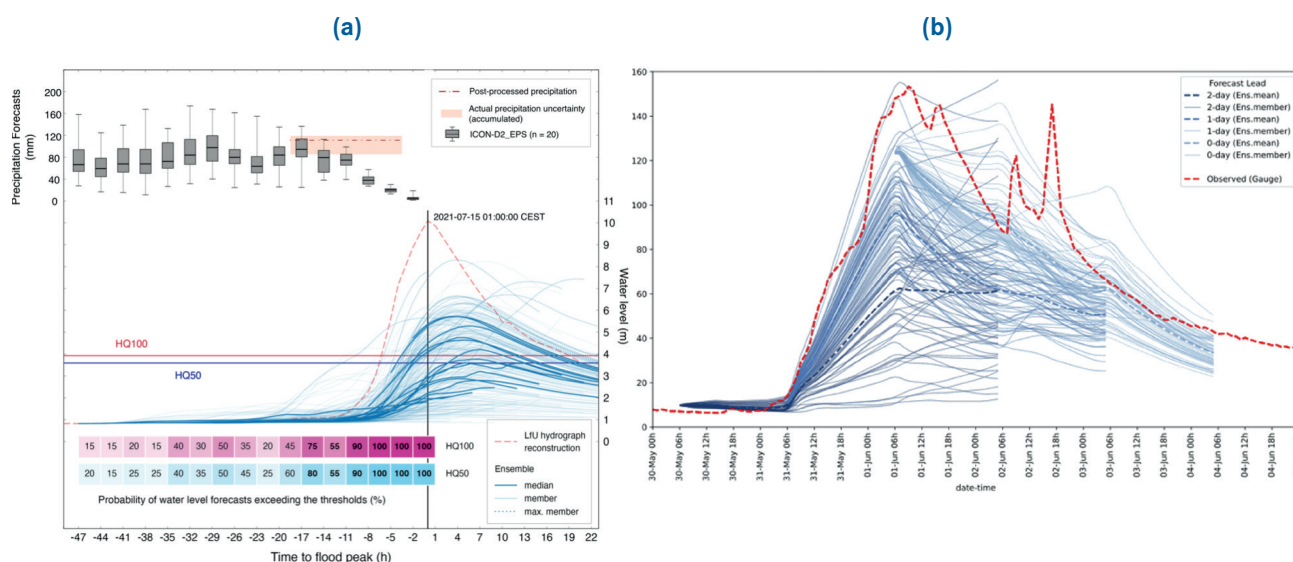


Figure 4: Comparison of ensemble predictions for water level and river discharge in two flood events: (a) 2021 summer flood at the Altenahr gauge, based on ICON-D2-EPS-mHM with 20 ensemble members (source: Najafi et al., 2024), and (b) May–June 2024 flood at the Salach gauge, using IFS-mHM (51 ensemble members).

Impact Forecasting and Maximum Lead-time map for the 2021 Ahr flood

Building on the forecasting chain for the Ahr Valley flood hindcast experiment (Najafi et al., 2024), high-resolution raster data outputs can be generated to support decision-making. These include exceedance probability maps for HQ100 and HQextreme thresholds, lead-time maps, and impact forecasts such as the number of inundated buildings, lengths of affected roads and railways, and human instability indicators, as described in Apel et al. (2022). For instance, the high-resolution lead-time map for the Ahr valley flood shows a time window ranging from 6 h to 30 h, which could have been used for the most likely outcome (i.e., ensemble median) (see Figure 5a). The maximum water level predictions indicate a lead-time map ranging from 24 h to 48 h before the forecasts exceed the HQ100 warning threshold (see Figure 5b). The study demonstrates that the mHM–RIM2D-based forecasting chain can be operated in near-real-time. Moreover, this approach shows strong potential for extension to other small- to medium-sized river basins across Germany, enhancing spatial coverage and operational flood preparedness.

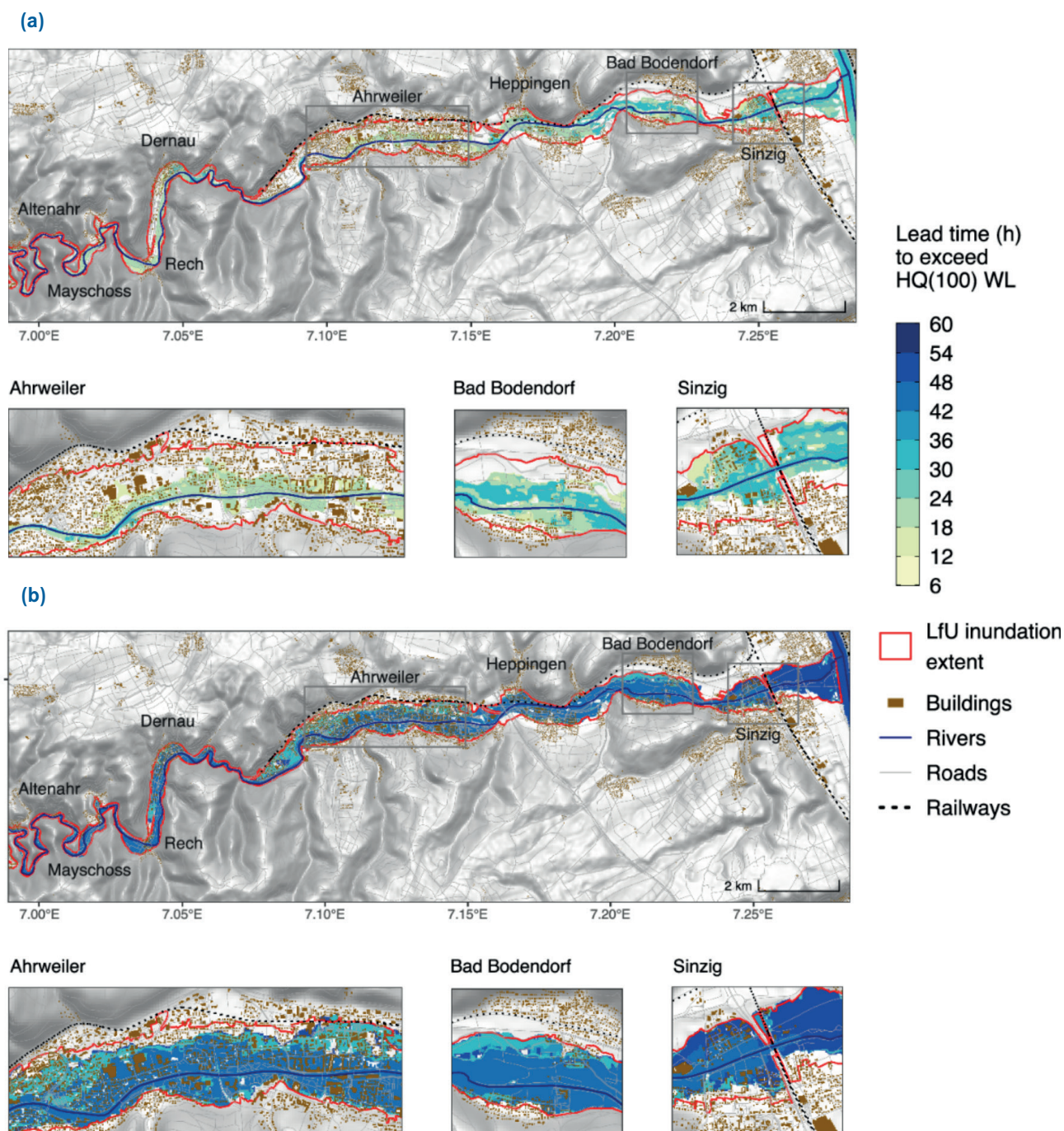


Figure 5: Lead-time maps indicating the maximum available time to exceed the HQ100 water level at Altenahr gauge calculated from ensemble (a) median water levels and (b) maximum water levels (Source: Najafi et al., 2024).

Flood Forecasting for the 2024 Fils flood

The peak discharge of the 2024 Fils flood at the gauge Salach was higher than the previous flood-of-record from 84 years of observations. According to the analysis, the 2024 flood's return period is around 175 years. The hydrological model ensemble underestimated the observed peak (see Figure 4b). Only the maximum en-

semble member reached comparable magnitudes. Figure 6 shows that with a 15-hour lead time, the simulated flood inundation forecast based on the maximum hydrological ensemble member matches the observed inundation extent in the area of Göppingen.

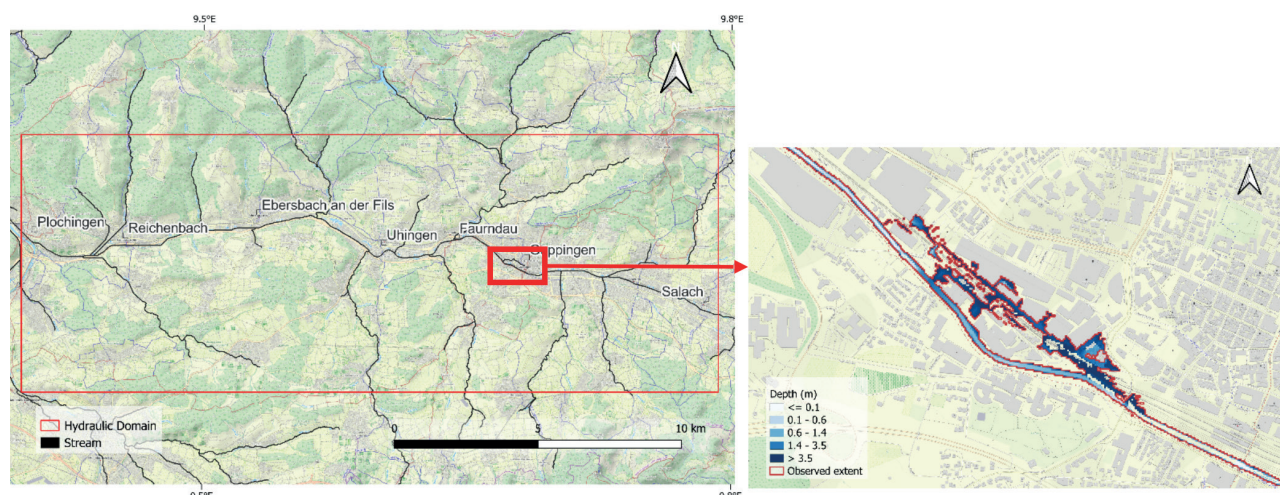


Figure 6: The forecasted maximum inundation extent on 1. June 2024 based on the maximum hydrological ensemble member from the IFS-mHM-RIM2D chain.

OUTLOOK

Feedback from the DWD has expressed strong interest in extending the model setup beyond the originally planned basins, in alignment with DWD's collaboration with the German flood forecasting centers (Hochwasservorhersage-Zentralen, HVZ). From a technical perspective, mHM is fully capable of operating across all gauged German river basins, including transboundary catchments. The model has already been applied at continental and global scales – including Europe-wide and global-scale implementations (see WMO report, 2024) demonstrating its scalability and suitability for broader applications. However, implementing ensemble streamflow forecasting across all basins in Germany – especially those with headwaters in neighboring countries – is currently limited by restricted public access to near-real-time meteorological data. Such data are critical for generating reliable hydrological initial conditions and ensuring the accuracy of forecasts in operational settings.

Using publicly available data from DWD, mHM can be applied to for 201 catchments located entirely within Germany (see Figure 7). For this purpose, we employ the existing daily model setup, which has already been calibrated as described by Boeing et al. (2022). This setup also offers the opportunity to compare mHM outputs with those from existing operational models, such as LARSIM, thereby contributing to model evaluation and further improvements.

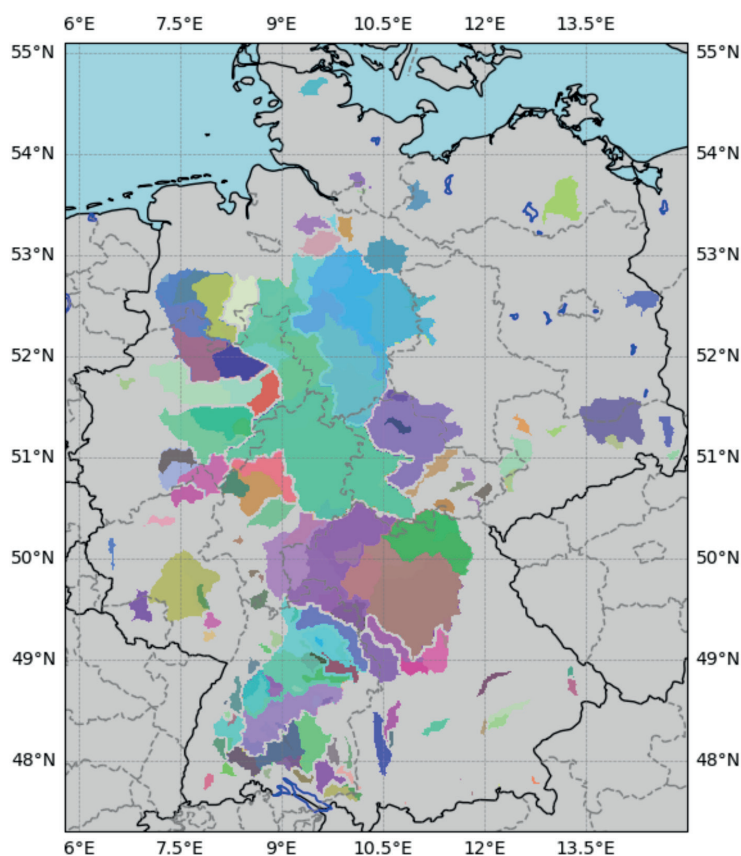


Figure 7: Locations of 201 basins in Germany for which flood forecasting with mHM model set-up described in Boeing et al. (2022) can be implemented.

CONCLUSIONS

We have developed a prototype impact-based flood forecasting and early warning system (FFEWS) and demonstrated its operational capability for flash flood forecasting of the Ahr 2021 and Fils 2024 floods. We demonstrated that the deadly potential of the 2021 Ahr flood could have been predicted at least 17 hours in advance. The prototype FFEWS is driven by operational weather forecast products from DWD and ECMWF consists of the hydrological model mHM and the hydrodynamic model RIM2D, enabling spatially explicit predictions of inundation areas, depths and impacts on population and built environment. For flood impact forecasting of the Ahr and Fils floods, we demonstrated decent accuracy and achieved simulation times less than 1% of the total event durations. This opens a window of opportunity extending operational forecast chains at state flood forecasting agencies beyond point-based peak flow and water stage predictions. A key limitation of current operational flood forecasting systems is the lack of probabilistic flood inundation and impact-based forecasting. These can, however, support issuing of tailored warning information and catastrophe management. In Germany, administrative decentralization and hydrological diversity have led to a system where most federal states operate their own State Flood Forecasting or Warning Centres, often supported by regional offices (Demuth & Rademacher, 2016).

The presented FFEWS is designed to showcase the potential advantages of the impact-based forecasting approach while promoting collaboration and co-design between scientific institutions and operational agencies.

DATA AVAILABILITY

Model setups and generated forecasts are open source and will be made available in the UFZ data portal once the ongoing publications are submitted.

Literature

- Apel, H., Benisch, J., Helm, B., Vorogushyn, S., and Merz, B. (2024). Fast urban inundation simulation with RIM2D for flood risk assessment and forecasting. *Frontiers in Water*, 6, 1310182–1310182. <https://doi.org/10.3389/FRWA.2024.1310182>
- Apel, H., Vorogushyn, S., and Merz, B. (2022). Brief communication: Impact forecasting for flood early warning—Lessons learned from the July 2021 event in Germany. *Natural Hazards and Earth System Sciences*, 22, 3005–3012. <https://doi.org/10.5194/nhess-22-3005-2022>
- Bates, P. D., Horritt, M. S., and Fewtrell, T. J. (2010). A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. *Journal of Hydrology*, 387(1–2), 33–45. <https://doi.org/10.1016/j.jhydrol.2010.03.027>
- Boeing, F., Rakovec, O., Kumar, R., Samaniego, L., Schrön, M., Hildebrandt, A., Rebmann, C., Thober, S., Müller, S., Zacharias, S., Bogen, H., Schneider, K., Kiese, R., Attinger, S., and Marx, A. (2022). High-resolution drought simulations and comparison to soil moisture observations in Germany. *Hydrol. Earth Syst. Sci.*, 26, 5137–5161, <https://doi.org/10.5194/hess-26-5137-2022>.
- de Almeida, G. A. M., Bates, P., Freer, J. E., and Souvignet, M. (2012). Improving the stability of a simple formulation of the shallow water equations for 2-D flood modeling. *Water Resources Research*, 48(5). <https://doi.org/10.1029/2011wr011570>
- Demuth, N and Rademacher, S, (2016): Chapter 5 - Flood Forecasting in Germany – Challenges of a Federal Structure and Transboundary Cooperation, *Flood Forecasting*, Academic Press, Pages 125–151, ISBN 9780128018842.
- Golding, B. (2022). *Towards the "Perfect" Weather Warning*. Springer. <https://doi.org/10.1007/978-3-030-98989-7>
- Merz, B., Kuhlicke, C., Kunz, M., Pittore, M., Babeyko, A., Bresch, D. N., Domeisen, D. I. V., Feser, F., Koszalka, I., Kreibich, H., Pantillon, F., Parolai, S., Pinto, J. G., Punge, H. J., Rivalta, E., Schröter, K., Strehlow, K., Weisse, R., and Wurpts, A. (2020). Impact Forecasting to Support Emergency Management of Natural Hazards. *Reviews of Geophysics*, 58(4), e2020RG000704. <https://doi.org/10.1029/2020RG000704>
- LfU. Hochwasser im Juli 2021. Tech. Rep., Landesamt für Umwelt (LfU) Rheinland-Pfalz [https://lfu.rlp.de/fileadmin/lfu/Wasserwirtschaft/Ahr-Katastrophe/Hochwasser_im_Juli2021.pdf\(2022\)](https://lfu.rlp.de/fileadmin/lfu/Wasserwirtschaft/Ahr-Katastrophe/Hochwasser_im_Juli2021.pdf(2022)).
- Najafi, H., and Coauthors, 2024: High-resolution impact-based early warning system for riverine flooding. *Nature Communications*, 15, 3726 (2024), <https://doi.org/10.1038/s41467-024-48065-y>
- Samaniego, L., Kumar, R., and Attinger, S. (2010). Multiscale parameter regionalization of a grid-based hydrologic model at the meso-scale. *Water Resources Research* 46.5, <https://doi.org/10.1029/2008WR007327>.
- Samaniego, L., Thober, S., Wanders, N., Pan, M., Rakovec, O., Sheffield, J., et al. (2019). Hydrological Forecasts and Projections for Improved Decision-Making in the Water Sector in Europe. *Bulletin of the American Meteorological Society*, 100(12), 2451–2472. <https://doi.org/10.1175/BAMS-D-17-0274.1>.
- Samaniego, L., Kumar, R., and Jackisch, C. (2011). Predictions in a data-sparse region using a regionalized grid-based hydrologic model driven by remotely sensed data. *Hydrology Research*, 42(5), 338–355. <https://doi.org/10.2166/nh.2011.156>
- World Meteorological Organization. (2015). WMO guidelines on multi-hazard impact-based forecast and warning services. WMO-No.1150. X
- World Meteorological Organization. (2018). Multi-hazard early warning systems: A checklist. Geneva, Switzerland: World Meteorological Organization.
- World Meteorological Organization. (2024). State of Global Water Resources 2023 (WMO-No. 1362). Geneva: WMO.
- Zink, M., Kumar, R., Cuntz, M., and Samaniego, L. (2017). A high-resolution dataset of water fluxes and states for Germany accounting for parametric uncertainty. *Hydrology and Earth System Sciences*, 21(3), 1769–1790. <https://doi.org/10.5194/hess-21-1769-2017>

Heat-vulnerable populations, the effects of heat on health in Germany, and approaches for better heat adaptation and resilience

Authors: Schneider, A.¹, Matthies-Wiesler, F.¹, Slesinski, S.C.¹ & Peters, A.¹

Affiliation(s):¹ Institute of Epidemiology, Helmholtz Zentrum München-German Research Center for Environmental Health (GmbH), Neuherberg, Germany

Email (Corresponding Author): alexandra.schneider@helmholtz-munich.de

INTRODUCTION

Heat stress causes the highest number of weather-related deaths globally (World Health Organization, 2024). In Europe, protecting the population from heat-related illness and death became a major policy priority in 2003, after unprecedented summer heat killed more than 70,000 people within three months in just 12 European countries³, including nearly 10,000 people in Germany (Robine et al., 2008). The progression of global climate change has increased the frequency and intensity of abnormally hot summers, including the summer of 2022 when nearly 50,000 excess deaths were recorded³ (Ballester et al., 2023). To support Germany's efforts to protect the population from the increasing threat of heat-related health effects, our research aims to provide relevant evidence for the German context on the effects of heat on health and heat-vulnerable populations. We also provide expertise and support for the development of policies, interventions, and communication strategies that aim to reduce the effects of heat on health in Germany.

Heat stress exposure and related adaptive capacity: Global inequalities

In a recently published systematic literature review, we demonstrated that social inequalities in exposure to heat stress (measured objectively and subjectively reported) and related adaptive capacity have been documented globally (Slesinski et al., 2025). The review identified and synthesized 123 relevant studies published between 2005 and 2024 from all global regions, with most coming from North America (47.2%), Asia (22.8%), and Europe (17.1%). Despite the geographic diversity of the research, similar patterns emerged across all studies: in general, those with lower socioeconomic status, children and young people, migrants, immigrants, and racial and ethnic minorities tended to have higher exposure to heat stress and lower adaptive capacity. Though a large proportion of the studies came from Europe, the evidence for the continent and for Germany is still limited. Most of the 10 German studies we identified focused on exposure to subjectively reported heat stress and heat-related adaptive capacity, while only two incorporated objective temperature measurements. The two German studies using objective measurements relied on land surface temperature and ambient temperature, neglecting to consider other important factors such as humidity, solar radiation, and wind speed. More research is needed in order to adequately characterize inequalities in exposure to objectively measured heat stress across Germany.

³ Specifically in Belgium, Croatia, England, France, Germany, Italy, Luxemburg, the Netherlands, Portugal, Slovenia, Spain, and Switzerland

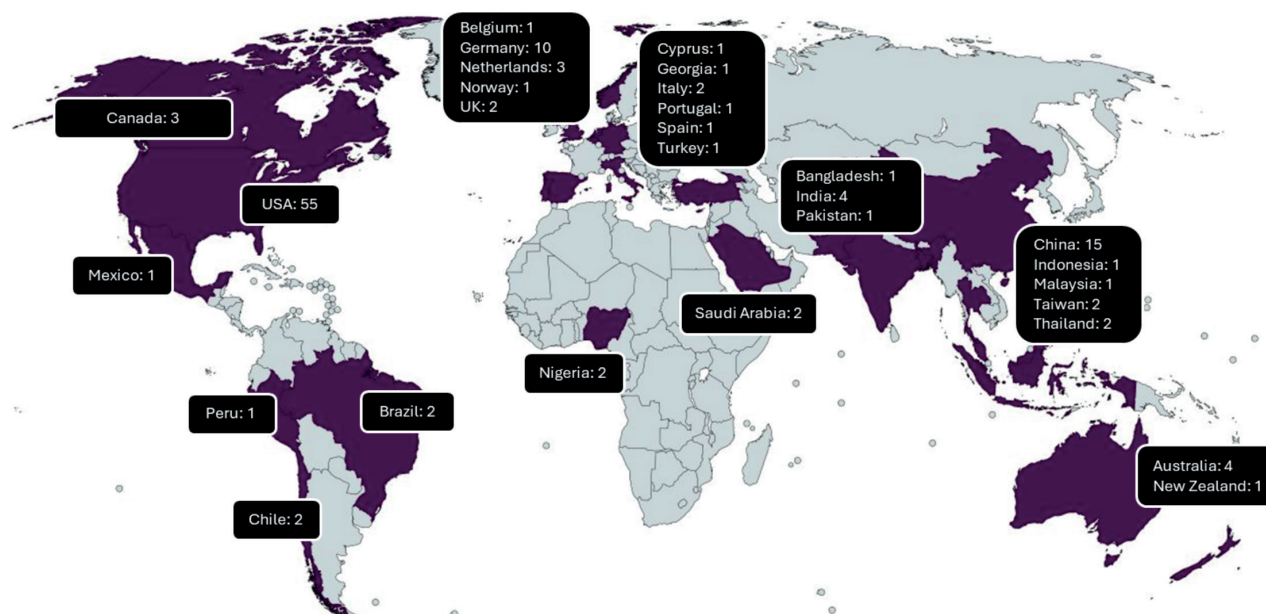


Figure 1: A map showing the number of studies documenting inequalities in heat stress exposure and related adaptive capacity by country. Studies published between January 2005 and January 2024 are included.

Despite these limitations, the available evidence indicates that in Europe, socially disadvantaged populations are generally more exposed to heat stress and less able to adapt. These socially disadvantaged groups are also more likely to experience chronic and non-communicable diseases such as cancers, cardiovascular disease, type 2 diabetes, chronic respiratory disease, and obesity, which increase their susceptibility to heat (McNamara et al., 2017; Sommer et al., 2015).

Heat-related mortality in Germany and the effectiveness of heat-health warning systems

To better understand how heat is affecting health in Germany and which groups are most vulnerable to poor health outcomes, we have implemented several studies to characterize heat-related mortality. In one study, we analyzed 2,050,764 deaths related to heart disease and 299,249 deaths related to lung disease that occurred in 380 German districts between 2000 and 2016 (Zhang et al., 2024). By considering average temperatures on the day of and day before each death, we were able to determine that the risk of death from heart disease increased by 24% (RR 1.24, 95% CI 1.23-1.26) and from lung disease by 34% (RR 1.34, 95% CI 1.30-1.38) during periods of extremely hot weather as compared to milder weather (quantified as a temperature increase from the 75th to the 99th percentile). The increase in risk of death during hot weather was higher for women and for people living areas that were more urbanized, had a higher proportion of foreigners, and had less green space. Another study focused specifically on determining the number of deaths in Germany that were caused by extreme heat during the summer of 2022 (Huber et al., 2024). We found that the previous estimate of 4,500 heat-related deaths was too low, and that in fact, high temperatures during the summer of 2022 likely caused 9,100 deaths. The previous estimate was based on weekly mortality and temperature averages, underestimating how many people died due to heat because of a lack of precision. Our study instead used daily temperatures and daily mortality counts to more accurately assess the effect of extreme heat during the summer of 2022. The findings of these studies clearly highlight the serious health risks posed by extreme heat in Germany.

Following the 2003 heatwave, the German government implemented a heat-health warning system, initiated in 2005. The warning system disseminates heat alerts through a government website, newsletters, smartphone applications, and through radio and television. To understand if Germany's efforts to protect the public's health through its heat-health warning system have had any effect, we analyzed the association between heat alerts and mortality in Germany's 15 largest cities (Feldbusch et al., 2025). We found significant variation in the effectiveness of these alerts in preventing deaths across cities. In Berlin, Frankfurt, and Hamburg, risk of mortality was significantly reduced when a heat alert was issued, while no significant association was shown for all other cities except for Duisburg, where heat alerts were associated with significantly increased risk of mortality. When combining the results of all 15 cities and taking into account city-level characteristics like the amount of recreational space available, the total population, and population density, we found that issuing a heat alert was associated with a 15% reduction in mortality risk (RR 0.85, 95% CI 0.75–0.97). These results emphasize the importance of considering local contexts when implementing heat-health interventions, and the importance of adjusting interventions to meet the needs of specific local populations.

Protecting people's health from heat: Developing heat-health action plans

Following the severe heatwave in Europe, the WHO Regional Office for Europe and several partners developed guidance for heat health action plans (Matthies et al., 2008). According to this guidance, heat-health action plans consist of eight core elements, ranging from heat early warning systems to protection measures in the medical and the social sector as well as in urban planning. This guidance was adapted to the German context in 2017 (BMU, 2017). In addition, the German Ministry of Health strengthened the heat health protection through guidance and recommendations specifically for the health sector in 2023 (BMG, 2023). Several policy actors, academic institutions, and scientists engaged in active dialogue to support these processes. As a part of the HI-CAM II project, we participated in these dialogues and provided scientific evidence and support.

Building on an update to heat-health action plan guidance in 2021 (WHO Regional Office for Europe, 2021), the WHO Regional Office for Europe is currently reviewing, and revising, and updating the guidance document and also integrating practical information and health messages. We have supported the WHO Regional Office in this work by providing scientific guidance, relevant recent evidence on heat effects on health (such as research results on the joint effects of air pollution and high temperatures [Chen et al., 2018], high nighttime temperatures and the risk of strokes [He et al., 2024], and the identification of social inequalities in relation to heat exposure and adaptive capacity [Slesinski et al., 2025]), and expertise in policy development and intervention design.

Reaching vulnerable groups: New advances in heat-health messaging

Communication and heat-health messaging are central to protecting people – especially at-risk groups – from the health effects of heat. However, developing appropriate messages and delivering them in an effective way to target audiences are very complex tasks. Socially isolated and older individuals, children, youths, athletes, and tourists are especially exposed to heat and particularly vulnerable to its health effects, yet difficult to reach with heat-health messages. Our research results and expertise have supported the development of a Ministry of Health-funded heat-health communication concept by the German Alliance for Health and Climate Change (KLUG e.V.). This heat-health communication concept capitalizes on the potential of human interaction and contacts in specific settings, such as between kindergarten teachers and children and parents or between pharmacists and their clients. Individuals who disseminate information during these interactions are called “multipliers.” This concept requires capacity building among multipliers and the development of messages

for strategically selected communication channels to ultimately raise awareness and influence behavior in the wider population and among at-risk individuals. We contributed to the development of guidance on how to reach at-risk groups which is now available on the website designed for communities, www.hitzeservice.de (Hitzeservice – Das Portal für Kommunen, n.d.).

Raising awareness: A web-based portal on health for students and teachers

Raising awareness among teachers and schoolchildren on health topics is an important part of education, as this can strengthen children's health literacy and increase healthy behavior early in life. By educating children and teachers about environmental health risks and explaining the link between climate change and health, it is possible to improve and deepen their understanding of extreme weather alerts, the need for preventive and protective behaviors, and the need for environmental protection and climate change mitigation. Awareness raising activities on health, and environment and health, for children and youths often also carry information and behavioral change into families and thus have an additional multiplying effect. To support these efforts in Germany, we developed evidence-based information and materials for a whole range of health topics targeted to children, youths, and teachers which are available on the AOK-supported portal www.clever-gesund-info.de. This flexible portal provides opportunities to complement existing health information with information on environmental and climate change related health risks, including heat risks. Here, Helmholtz Munich draws on wide-ranging expertise to translate relevant research results into interactive learning materials, such as health effects of heat and respective adaptation measures or the interactions between plant-based nutrition, and physical activity, health and climate change mitigation.

CONCLUSIONS

Heat is an important environmental health risk in Germany. Our research shows that extreme heat exposure is not equally distributed across populations and that it has caused tens of thousands of deaths in Germany since the year 2000. While existing heat-health warning systems are preventing some of the health impacts of heat in some parts of the country, more action is needed to ensure that evidence-based, appropriate and timely heat-health messages are received by those who need them. For this, close collaboration between epidemiologists, medical professionals and communication experts is needed to design effective communication strategies and campaigns for dissemination through multiple channels and information “multipliers”. Raising awareness through educational materials for schools, students, and teachers, can lay an important foundation for the younger generation. To further reduce the health effects of heat, governments can remove structural and cultural barriers to the adoption and implementation of heat adaptation measures. Reducing heat in deprived neighborhoods and in urban heat islands through structural interventions like increasing greenness can greatly benefit socially disadvantaged people and reduce environmental and health inequalities. While the assessment of social dimensions in a community can add valuable information to the development of heat-health action plans and heat-health protection measures (both behavioral and structural), it is important that these measures avoid worsening existing social or health inequalities (e.g. through green gentrification). Heat-health interventions of all kinds should take an integrated and holistic approach, actively engage a range of sectors, consider social factors, and adopt an intersectional perspective.

Literature

- Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R. F., Pegenaute, F., Herrmann, F. R., Robine, J. M., Basagaña, X., Tonne, C., Antó, J. M., & Achebak, H. (2023). Heat-related mortality in Europe during the summer of 2022. *Nature Medicine*, 29(7), Article 7. <https://doi.org/10.1038/s41591-023-02419-z>
- Bundesministerium für Gesundheit (BMG). (2023). Hitzeschutzplan für Gesundheit des BMG. https://www.bundesgesundheitsministerium.de/fileadmin/Dateien/3_Downloads/H/Hitzeschutzplan/BMG_Hitzeschutzplan.pdf
- Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMU). (2017). Handlungsempfehlungen für die Erstellung von Hitzeaktionsplänen zum Schutz der menschlichen Gesundheit. https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/hap_handlungsempfehlungen_bf.pdf
- Chen, K., Wolf, K., Breitner, S., Gasparrini, A., Stafoggia, M., Samoli, E., Andersen, Z. J., Bero-Bedada, G., Bellander, T., Hennig, F., Jacquemin, B., Pekkanen, J., Hampel, R., Cyrus, J., Peters, A., & Schneider, A. (2018). Two-way effect modifications of air pollution and air temperature on total natural and cardiovascular mortality in eight European urban areas. *Environment International*, 116, 186–196. <https://doi.org/10.1016/j.envint.2018.04.021>
- Feldbusch, H., Schneider, A., Matthies-Wiesler, F., Matzarakis, A., Peters, A., Breitner-Busch, S., & Huber, V. (2025). Assessing the effectiveness of the heat health warning system in preventing mortality in 15 German cities: A difference-in-differences approach. *Manuscript Submitted for Publication*.
- He, C., Breitner, S., Zhang, S., Huber, V., Naumann, M., Traidl-Hoffmann, C., Hammel, G., Peters, A., Ertl, M., & Schneider, A. (2024). Nocturnal heat exposure and stroke risk. *European Heart Journal*, 45(24), 2158–2166. <https://doi.org/10.1093/eurheartj/ehae277>
- Hitzeservice – Das Portal für Kommunen. (n.d.). Retrieved March 27, 2025, from <https://hitzeservice.de/>
- Huber, V., Breitner-Busch, S., He, C., Matthies-Wiesler, F., Peters, A., & Schneider, A. (2024). Heat-Related Mortality in the Extreme Summer of 2022. *Deutsches Ärzteblatt International*, 121(3), 79–85. <https://doi.org/10.3238/arztebl.m2023.0254>
- Matthies, F., Bickler, G., Cardenosa Marin, N., & Hales, S. (2008). Heat-health action plans: Guidance (EUR/07/5067942). WHO Regional Office for Europe. <https://iris.who.int/bitstream/handle/10665/107888/9789289071918-eng.pdf?sequence=1>
- McNamara, C. L., Toch-Marquardt, M., Balaj, M., Reibling, N., Eikemo, T. A., & Bambra, C. (2017). Occupational inequalities in self-rated health and non-communicable diseases in different regions of Europe: Findings from the European Social Survey (2014) special module on the social determinants of health. *European Journal of Public Health*, 27(suppl_1), 27–33. <https://doi.org/10.1093/eurpub/ckw223>
- Robine, J.-M., Cheung, S. L. K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J.-P., & Herrmann, F. R. (2008). Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus Biologies*, 331(2), 171–178. <https://doi.org/10.1016/j.crv.2007.12.001>
- Slesinski, S. C., Matthies-Wiesler, F., Breitner-Busch, S., Gussmann, G., & Schneider, A. (2025). Social inequalities in exposure to heat stress and related adaptive capacity: A systematic review. *Environmental Research Letters*, 20(3), 033005. <https://doi.org/10.1088/1748-9326/adb509>
- Sommer, I., Griebler, U., Mählknecht, P., Thaler, K., Bouskill, K., Gartlehner, G., & Mendis, S. (2015). Socioeconomic inequalities in non-communicable diseases and their risk factors: An overview of systematic reviews. *BMC Public Health*, 15(1), 914. <https://doi.org/10.1186/s12889-015-2227-y>
- WHO Regional Office for Europe. (2021). *Heat and health in the WHO European Region: Updated evidence for effective prevention*. WHO Regional Office for Europe. <https://iris.who.int/bitstream/handle/10665/339462/9789289055406-eng.pdf?sequence=1>
- World Health Organization. (2024, May 28). *Heat and health*. World Health Organization. <https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health>
- Zhang, S., Breitner, S., Donato, F. de', Stafoggia, M., Nikolaou, N., Aunan, K., Peters, A., & Schneider, A. (2024). Heat and cause-specific cardiopulmonary mortality in Germany: A case-crossover study using small-area assessment. *The Lancet Regional Health – Europe*, 46. <https://doi.org/10.1016/j.lanepe.2024.101049>

Operationalization of a Generalized Health Model for Heat Stress

Authors: Hertel, D., Schlink, U., Wollschläger, N.

Affiliation(s): ¹ Helmholtz Centre for Environmental Research – UFZ, Leipzig.

Email (Corresponding Author): uwe.schlink@ufz.de

INTRODUCTION

In recent years, health research has undergone a paradigm shift, focusing more on individual risks in the wider context of natural systems. This approach has been conceptualized in a generalized health model, for which an interactive toolbox has been suggested (Hertel et al., 2023). This includes simulations of thermal burden in high temporal and spatial resolution for urban regions.

For this purpose, the foundations for a publicly accessible web application were developed, which is intended to support municipal climate adaptation and acts as an analysis tool for the local thermal situation. Technical realizations that contribute to this toolbox were the subject of the HI-CAM Phase 2 project.

DATA AND METHODS

A web app was implemented in R (v4.0.3), based on the open source R package ‘Shiny’ (v1.7.4). The tool was initially hosted locally via the Shiny server in order to be able to carry out extensive tests on the layout, performance and pre-processing of the data to be imported. The main input data comprise simulations with the PALM-4U urban climate model (<https://palm.muk.uni-hannover.de/trac/wiki/palm4u>), as well as age structure data from the City of Leipzig (Leipzig Office for Statistics and Elections, population register), which are stored on an sftp server at UFZ. The algorithm for heat attribution developed in HI-CAM Phase 1 (Hertel and Schlink (2019a, 2019b) and a status quo scenario described in Helbig et al. (2023) were used to post-process the data.

A container was created using Docker technology, transferred to Gitlab, and hosted on a publicly accessible UFZ server (https://web.app.ufz.de/MethBox_Hitze_Gruenau/). The current app version was created for 12 August 2022, during a pronounced heat episode, using Leipzig-Grünau-Nord as an example. In addition, the thermal effects of various green design scenarios for open spaces in an urban neighborhood (for example at Titaniaweg) can be visualized and analyzed.

High-resolution urban climate simulations (PALM-4U) are planned to be combined with health data from the German National Cohort (NAKO) health study center Leipzig. The required input data for PALM-4U were already available from our work in HI-CAM Phase 1 (see also Hertel et al. in final report HI-CAM Phase 1). For the Phase 2, a 5 x 5 km simulation area (spatial resolution 5 m) was specified. This area corresponds to the INSPIRE (standardized European spatial data infrastructure) grid cell in which most of the NAKO study participants in Leipzig were located. The INSPIRE grid was provided by the NAKO Environmental Data Unit (EDU) at HMGU. To make an association analysis possible using NAKO health data from the study center in Leipzig (e.g. cogni-

tive function, blood pressure, etc.) for the period 2014–2019, a representative heat episode was simulated with PALM-4U for each year that results in urban heat patterns. For comparability, only heat episodes that occurred under similar weather conditions were selected. The DWD's 'Objective Weather Situation Classification' and a visual assessment of GFS reanalysis weather data (https://wetter3.de/archiv_gfs_dt.html) were used as selection criteria. The static vertical profiles for mixing ratio and potential temperature required for PALM-4U initialization were extracted from radiosonde ascents (weather.uwyo.edu/upperair/sounding.html).

RESULTS

The conceptual framework combining micro-meteorological simulations of heat with health aspects was operationalized for the example of socio-demographic data and visualized in a WebApp (see Figure 1).

MethBox-Hitze (v1.3, Leipzig-Grünau-Nord)

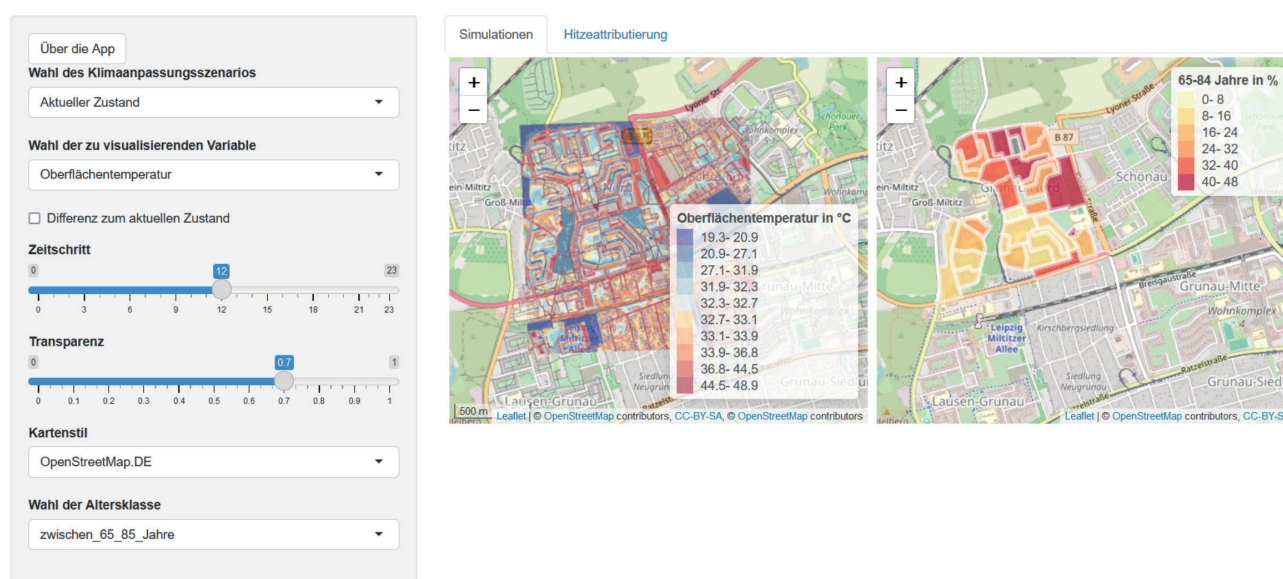


Figure 1: Screenshot of the WebApp operationalizing the joint consideration of heat and socio-demographic characteristics of inhabitants of the urban quarter Grünau-Nord on 12 August 2022.

An advantage of PALM-4U is the ability to simulate larger urban regions. For Leipzig, the simulation area (5km x 5km) comprises 1000 x 1000 grid cells and covers the urban region of Leipzig (suburbs are not included). The results are available in the form of netCDF files for the 6 years 2014–2019 that are compatible to the NAKO study periods. The average level of physiologically equivalent temperature (PET) suggests the occurrence of hot-spots of thermal burden in Leipzig. Low values of temporal variability in these pixels indicate the stability of these spatial PET patterns over the considered 6 years (see Figure 2).

CONCLUSIONS

The results demonstrate the applicability of urban micro-meteorological simulations (using e.g. the PALM-4U software) for the investigation of adverse health effects of heat. It also allows for studies of environmental justice that consider different levels of heat exposure for different socio-demographic groups, such as age groups (see WebApp in Figure 1).

Repeated simulations of urban thermal conditions for a period of 6 years confirmed the existence of hot-spots of poor thermal comfort (see Figure 2, left). These hot-spots are rather stable in the densely populated downtown area, where they have low variability (see Figure 2, right). In contrast, elevated variability can be realized near green areas (parks, allotment gardens, meadows, ...).

This observation indicates that, firstly, the heat burden depends strongly on the local conditions and, secondly, the repeated and persistent occurrence of heat over several summers (i.e. low variability of heat) also depends on the surroundings. Both extreme heat and repeated heat are interesting factors to combine with health outcomes, such as those from the NAKO study, which are related to the surroundings of residences of study participants. This HI-CAM output stimulates future cooperation and research on the health effects of heat in urban regions.

Moreover, projections of health risks are possible under conditions of future climate and modified urban structures resulting from future urban and landscape development.

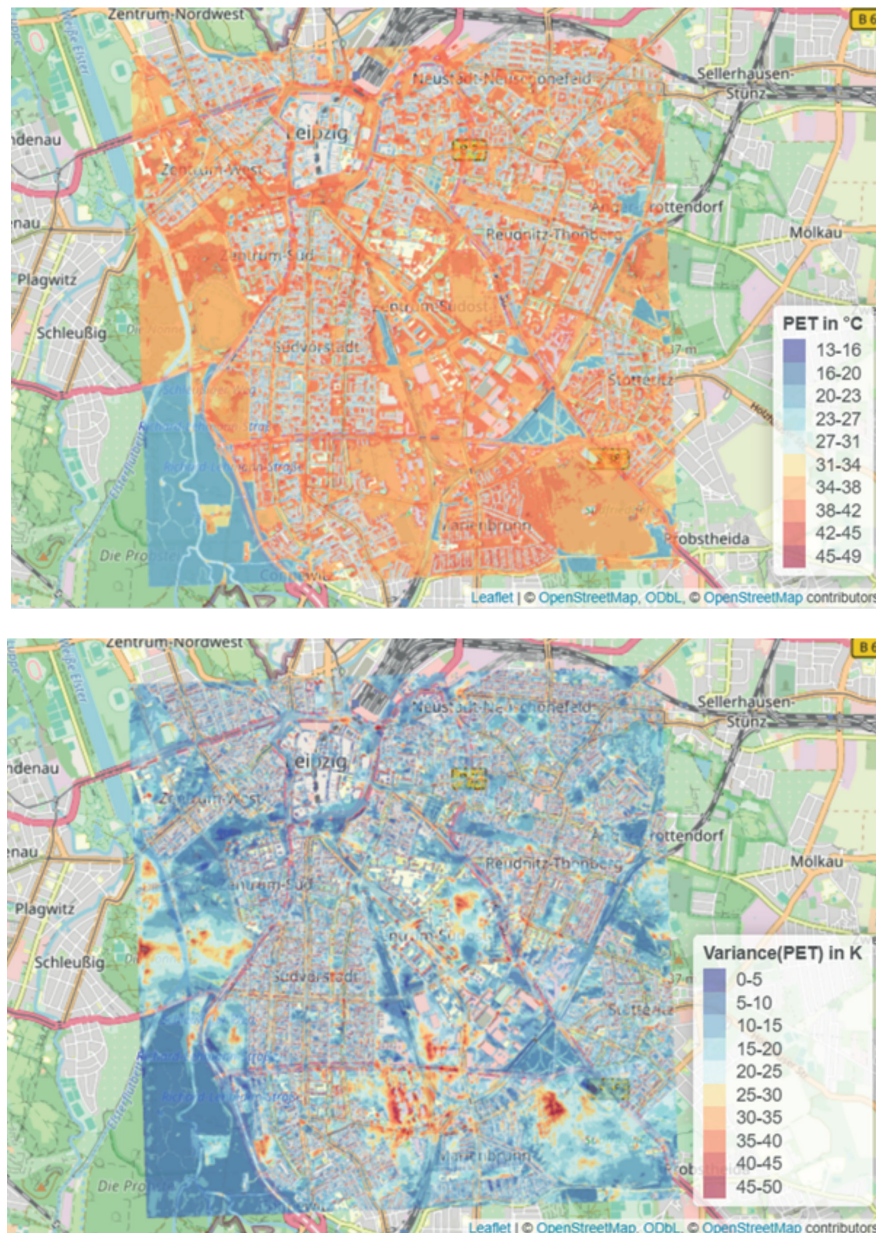


Figure 2: Simulated physiologically equivalent temperature (PET at 12:00) in Leipzig: average over extreme heat periods from 2014-2019 (upper), interannual variability (lower plot).

Data Availability

The WebApp is available online at https://web.app.ufz.de/MethBox_Hitze_Gruenau.

Simulations of PALM-4U are available on request to enable future association analyses using NAKO health data.

Literature

Helbig, C., Pöbneck, J., Hertel, D., Sen, Ö. O. (2023): Potential of 3D Visualisation and VR as Boundary Object for Redesigning Green Infrastructure – a Case Study. In: Dutta, S., Feige, K., Rink, K., Zeckzer, D. (Hrsg.): Workshop on Visualisation in Environmental Sciences (EnvirVis), Proceedings. Eurographics, S. 41-49. <https://doi.org/10.2312/envirvis.20231105>

Hertel, D., Pöbneck, J., Kabisch, S., Schlink, U. (2024): Hitzestress in Stadtquartieren – Methodik und empirische Belege unter Nutzung des Planetary-Health-Ansatzes. In: Kabisch, S., Rink, D., Banzhaf, E. (Hrsg.) Die resiliente Stadt: Konzepte, Konflikte, Lösungen. Springer Spektrum, Berlin, Heidelberg, S. 247 – 266, https://doi.org/10.1007/978-3-662-66916-7_16

Hertel, D., Pöbneck, J., Kabisch, S., Schlink, U. (2023): Planetary Health Modell zur Reduktion von Hitzestress auf Quartiersebene. DBU-Abschlussbericht AZ: 37993/01. Zenodo, <https://doi.org/10.5281/zenodo.10143420>

Hertel, D., Schlink, U. (2019a): Decomposition of urban temperatures for targeted climate change adaptation. Environ. Modell. Softw. 113, 20 – 28, <https://doi.org/10.1016/j.envsoft.2018.11.015>

Hertel, D., Schlink, U. (2019b): How to convert urban energy balance into contributions to urban excess temperatures? MethodsX 6, 132 – 142, <https://doi.org/10.1016/j.mex.2018.12.015>

Kabisch, S., Schlink, U., Hertel, D., Pöbneck, J. (2023): Lokalem Hitzestress im Quartier zielgenau begegnen. 3D-Stadtklimasimulationen zur Gestaltung schattiger und einladender Grünräume. Transforming Cities 3, 66 – 70



CLUSTER III

CLUSTER III: COMMUNICATION

Office:

Markgrafenstraße 22
10117 Berlin
Germany

www.helmholtz-klima.de

📧 [helmholtz_klima](#)

🌐 [helmholtzklima](#)

🐦 [helmholtzklima.bsky.SOCIAL](#)

✂️ [HELMHOLTZKLIMA](#)

📺 [@HELMHOLTZKLIMA](#)

INTRODUCTION

In the first project phase, the Communication Cluster of the Helmholtz Climate Initiative established a dynamically growing information hub in 2020 and 2021. The goal of this hub was to centrally communicate systemic climate research from all six research fields and the 15 centers involved in the initiative, while also facilitating cross-cutting communication between research fields and centers. In doing so, a comprehensive, Helmholtz-wide platform for information, communication, and expertise was created. This aligns with the Helmholtz Association's mission to address major societal challenges through a systemic approach.

This is also reflected in the following four core objectives defined by the Steering Board of the Helmholtz Climate Initiative for the Communication Cluster - all of which were achieved during the first phase:

- Establishment of an expert database of about 100 Helmholtz climate researchers who act as direct contacts for politicians, the media and the public
- Creation of fact sheets on current climate-relevant issues, especially for political communication
- Creation of the first social media formats (e.g. YouTube clips featuring selected experts)
- Continuation of discussions with external partners through joint communication formats

Following the decision to continue the communication activities of the Helmholtz Climate Initiative at the end of 2021, the hub was maintained and further expanded from early 2022 until the conclusion of the second phase at the end of 2023.

SPECIAL FRAMEWORK CONDITIONS

One of the central tasks during the second phase was to explore the potential continuation of the Helmholtz Climate Initiative. To this end, a Future Workshop was held in March 2023, involving all relevant stakeholders from the Helmholtz Association. Based on the outcomes of this workshop, a concept envisioning the long-term continuation of the Communication Cluster in the form of a dialogue platform called Helmholtz KLIMA was developed.

Interim funding through the end of 2027 was secured via bilateral financial commitments from all 18 Helmholtz Centers and the Head Office of the Helmholtz Association. The discussion surrounding the future direction and funding structure – an inherently time- and labor-intensive process due to the complexity of Helmholtz-wide coordination – led to a shift in the Communication Cluster's activities.

From March 2023 onward, day-to-day operations were reduced in favor of strategic planning and further development.

Approach and Structure – the underlying Communication Concept

Communication is a central component of climate-related research at Helmholtz and has been considered an integral part of the Climate Initiative from the very beginning. The goal has always been a needs-oriented, solution-focused, and agile form of communication that brings together research and societal actors.

At the heart of this approach is the further development of the Climate Dialogue Platform, which is based on the following three principles:

- Monitoring current societal and political climate debates
- Targeted exchange with stakeholders (from politics, business, media, and the public) to identify specific needs
- Selection of topics and formats based on concrete demand

This led to a broad portfolio of instruments, which continued to be used in the second phase, though to a lesser extent:

- Informational content such as explainer videos, fact sheets, and position papers
- Dialogue formats like workshops, stakeholder dialogues, panel discussions, or creative formats
- Advisory services for policymakers and business, e.g. through research breakfasts, background talks, and the expert database
- Media training for scientists

The central platform remained the website www.helmholtz-klima.de, which was increasingly tailored to specific topics and target groups. This was supported by social media, press relations, and campaigns, all flexibly adapted as needed.

Networks are essential:

Both internally (e.g. with SynCom, REKLIM, TERENO, MOSES, and the Climate Offices) and externally (e.g. with the German Climate Consortium, DWD, klimafakten.de), existing structures were continuously expanded and strengthened.

Centers, initiatives, and projects contributed specific input to the dialogue platform during the second phase – depending on topic, audience, and available resources. Their close involvement remained key to the initiative's success.

NETWORKING WITH OTHER CLIMATE COMMUNICATION STAKEHOLDERS AND POLITICAL COMMUNICATION

Over the years, a close-knit network has developed, which has been actively maintained and expanded by the Climate Initiative. In addition to the German Climate Consortium, the German Meteorological Society, the German Weather Service, the Extreme Weather Congress, and klimafakten.de, this network also includes representatives from other research institutions such as the Max Planck Society, the Leopoldina, and the IPCC. The German Alliance for Marine Research, the coordinator of the Helmholtz research field “Earth and Environment”, and SynCom are located in close proximity, ensuring a particularly close exchange.

Since climate topics continue to play a central role in the research field “Earth and Environment” through the program “Changing Earth – Sustaining our Future”, there has also been a regular exchange with the communication leads of the seven associated Helmholtz centers.

In the field of political communication, the existing network and contacts have been continuously expanded. Here, the Communication Cluster provides monitoring of political initiatives and events in Berlin on behalf of the centers and keeps them informed about current political developments.

MARKETING OF THE PARTICIPATING CENTERS AND FURTHER HELMHOLTZ CLIMATE RESEARCH

The website and press work of the Helmholtz Climate Initiative make all 15 participating centers as well as the Helmholtz Association visible – through the website, graphics, and presentations. Short profiles of other Helmholtz climate research initiatives and links to the press offices and media libraries complement the offering.

The Communication Cluster maintains close contact with the press offices of the centers to coordinate inquiries and expert referrals. Together with the centers, it forms a strong network for topic monitoring, knowledge synthesis, stakeholder communication, and expert training – thus enhancing the visibility of the centers on established communication channels.

PRESS RELATIONS

Press work was further expanded and continued but still serves as a complementary service to the press offices of the centers, acting as an intermediary between them. The Communication Cluster remains the first point of contact for journalists seeking guidance, contact mediation, or cross-center and cross-topic context on climate issues. Press inquiries were regularly received and answered in close coordination with the centers' press offices, or Helmholtz scientists were referred to newspapers, magazines, radio, or TV stations for interviews or expert discussions.

As of December 2023, the press distribution list included 231 contacts of journalists and media representatives.

MONITORING

Daily media and topic monitoring takes place using these services: Press Relations (via the Berlin office), Echobot (via Hereon), Science Information Service (idw), dpa-Agenda, Tagesspiegel-Background.

CONTINUATION OF THE WEB PRESENCE (GERMAN AND ENGLISH)

The website www.helmholtz-klima.de was also the central communication tool of the Helmholtz Climate Initiative during the second phase, consolidating social media, networking activities, events, expert placement, media library, press portal, and climate FAQ. It attracted more than 340,000 visitors and 580,000 page impressions.

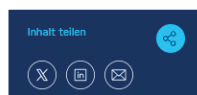
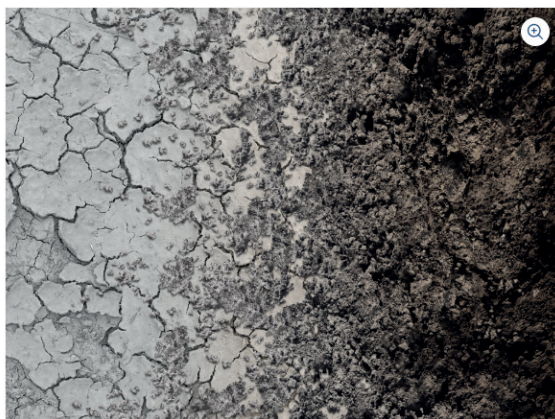
The core elements of the website were:

- Current articles and interviews with HI-CAM scientists (about 50 additional articles published as of December 2023 bringing the total to 140 including Phase 1)
- A database of experts with around 120 entries of Helmholtz climate scientists
- Media library with videos, fact sheets and infographics (about 13,000 downloads as of December 2023 and in total 21,000 combined with Phase 1)
- Press portal with press releases from the Helmholtz Association on climate issues, press contacts (including contacts at the centers), and a media library with a download section
- Climate FAQs with answers to relevant, frequently asked questions about climate change
- Climate calendar with upcoming climate-related events
- Visualization of further Helmholtz climate research and of the 15 participating centers

Startseite | Klimadialog | Aktuelles | Synthesebericht zum Sechsten IPCC-Sachstandsbericht

20.03.2023

Synthesebericht zum Sechsten IPCC-Sachstandsbericht



Am Montag hat der Weltklimarat (IPCC) seinen sechsten Sachstandsbericht veröffentlicht. Er fasst die seit 2018 erschienenen Berichte zu *Naturwissenschaftliche Grundlagen des Klimawandels (WG I)*, *Folgen des Klimawandels, Anpassung und Verwundbarkeit (WG II)* und *Minderung des Klimawandels (WG III)* sowie die drei Sonderberichte über 1,5 °C globale Erwärmung (SR1.5), über Klimawandel und Landsysteme (SRCCL) und über den Ozean und die Kryosphäre (SROCC) zusammen.

DEVELOPMENT OF SOCIAL MEDIA PLATFORMS

The Helmholtz Climate Initiative is mainly active on the following social media platforms: Twitter, Instagram, Mastodon, LinkedIn and YouTube.

With around 5.015 followers (as of December 2023), Twitter is the social media presence of the Helmholtz Climate Initiative with the greatest outreach. This is due both to the active operation of the account and to the content and target audience of the platform.

Besides Twitter, Instagram is the social media platforms with the second highest number of followers (3,371), followed by Mastodon (2,750) and LinkedIn (2,576). Additionally, a YouTube channel is operated, where 16 specially produced videos have been published, reaching a total of 842 subscribers (as of December 2023).

Warum die Arktis so viel schneller schmilzt als die Antarktis 10.941 Aufrufe • vor 1 Jahr	Wie uns das Leben im Boden helfen kann 3753 Aufrufe • vor 2 Jahren	Dürre in Deutschland? 24.395 Aufrufe • vor 5 Jahren

CREATION OF FACT SHEETS ON CURRENT TOPICS

Climate knowledge presented concisely and visually – that is the idea behind the two-page fact sheets of the Helmholtz Climate Initiative. They present individual climate issues in a clear, accessible and visually appealing way. The fact sheets close by showing the area in which Helmholtz is researching the relevant topic. The following four topics have been implemented in the second phase:

- Allergies
- Wetlands and moors
- Heat pump
- Carbon dioxide



A NEWSLETTER PROVIDES THE LATEST INFORMATION ON CLIMATE RESEARCH

The Helmholtz Climate Initiative's monthly newsletter currently has around 900 subscribers. It summarizes the most important topics from the recent reports about Helmholtz climate research from the last four weeks. It also announces interesting opportunities from partner organizations and relevant events.

MEDIA TRAINING FOR HELMHOLTZ CLIMATE SCIENTISTS

The Communication Cluster offers three types of media training for the scientists of the Climate Initiative:

- Two-day media training
- Two-day moderation training
- Individual media training lasting several hours

On the one hand, the training prepares the scientists for interactions with media representatives. On the other hand, it builds up and/or improves their media skills. A total of 6 media training courses were held in cooperation with an external service provider.

EVENTS

Due to conceptual realignment, fewer events were held than in previous years. Nevertheless, various formats were implemented under the leadership or involvement of the Climate Initiative:

- A research breakfast on the new UBA (Federal Environment Agency) figures, together with the German Climate Consortium and the UBA
- The first Climate Cantina on the topic “Climate Protection and Agriculture in Rewetted Peatlands,” together with Thorsten Sachs (GFZ), involving 20 employees of members of the Bundestag
- A concert by the Orchestra of Change with participation from HEREON
- A future workshop involving all relevant stakeholders from the Helmholtz Association

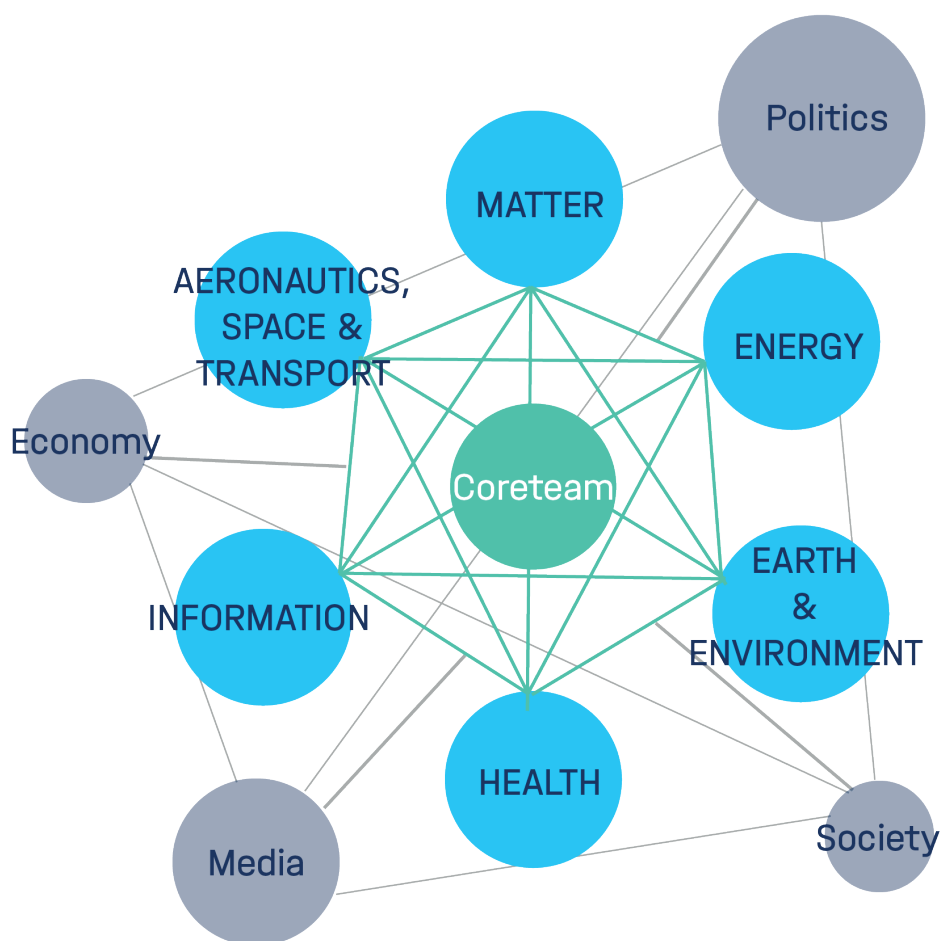
Central to the further development of the Climate Initiative was the Future Workshop in March 2023 in Berlin, attended by a total of 64 participants from across the Helmholtz Association to jointly discuss and design a concept for the continuation of the Climate Initiative. This continuation refers solely to Cluster III Communication, whose funding ended at the close of 2023. Clusters I and II will continue to complete their research projects until the end of 2024.

Key results of the workshop from the perspective of the Communication Cluster of the HKI are:

- Helmholtz KLIMA should network scientists both across centers and research fields as well as beyond the Helmholtz Association with partners to enable new research collaborations. Network events, workshops, a digital platform, and more should support this;
- Helmholtz KLIMA should engage in dialogue with politics, media, and society to identify specific needs for dialogue or information and communicate in a needs- and solution-oriented way, including through events, policy advice, a website, and social media platforms
- Helmholtz KLIMA thereby occupies a unique role within the German scientific landscape. It creates a distinctive feature for the highly complex, systemic climate-related research of the Helmholtz Association;
- There will be three focal topics in the future: Climate and Energy, Climate and Health, and Climate and Cities.

SUMMARY AND OUTLOOK

The second phase of the Communication Cluster was characterized by strategic and conceptual development aimed at ensuring a long-term continuation of the dialogue platform beyond the end of 2023. This aim was achieved, based on the Future Workshop in March 2023 and the approval of all 18 centers for the resulting overall concept, as well as bilateral financing commitments from the Helmholtz Association Head Office, initially through the end of 2027. The concept foresees a dialogue platform called Helmholtz KLIMA, which, as a genuine cross-sectional initiative, bundles climate-relevant research from all research areas and centers of the Helmholtz Association and brings it into dialogue with political decision-makers, media, journalists, economy and society.



To implement this realignment, the transition from the Helmholtz Climate Initiative to Helmholtz KLIMA was initiated in 2023. With the funding for the Communication Cluster ending at the close of 2023, the cluster will be restructured as the Helmholtz KLIMA Dialogue Platform from 2024 onward.