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Improving science-policy-practice collaboration

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Abstract: Climate resilient infrastructure systems

Over the course of 2021, UBA commissioned a series of workshops on the topic of climate resilient infrastructure systems to discuss why research outputs are not more consistently transferred into practice of infrastructure operation. This paper presents the outcomes of this process. It presents barriers for successful transfer of research outputs into practice and for each barrier provides recommendations to overcome them. The identified key lessons for facilitating climate resilience of infrastructure systems are: (i) A better approach to knowledge co-production is needed at all stages of research, including the explicit inclusion of a trust-building phase between researchers and users; (ii) Frameworks related to funding, standards, and regulations need to be systematically assessed to determine whether and why they might facilitate or hinder the uptake of research results; (iii) Existing capacity to raise Technology Readiness Levels needs to be increased, e.g., by providing funding programs that support long-term collaboration among successful consortia; (iv) There is a need for European and national services to support long-term access to research results; (v) More capacity needs to be provided for education and training of users; (vi) There is a need for improved cross-sector applicability through harmonization of methods, data formats, and terminology; and (vii) A mechanism is needed to support the extension of already well-established (but potentially sector-specific) research results for critical infrastructure systems.

The target audiences for these recommendations are funding bodies, policy makers, and standardization bodies that can influence the framework conditions under which infrastructure resilience research takes place, research project coordinators and other academic/researcher institutions who are often the main responsible for the design of research projects, and practitioners who design and manage (critical) infrastructure systems.

Kurzbeschreibung: Klimaresiliente Infrastruktursysteme

Im Laufe des Jahres 2021 hat das UBA eine Reihe von Workshops zum Thema klimaresiliente Infrastruktursysteme in Auftrag gegeben, um zu diskutieren, warum Forschungsergebnisse nicht konsequenter in die Praxis übertragen werden. Das vorliegende Papier stellt die Ergebnisse dieses Prozesses vor. Es stellt Hindernisse für einen erfolgreichen Transfer von Ergebnissen in die Praxis dar und gibt Empfehlungen zu deren Überwindung. Die wichtigsten Erkenntnisse zur Förderung der Klimaresilienz von Infrastruktursystemen sind: (i) In allen Phasen der Forschung ist ein besserer Ansatz für die Ko-Produktion von Wissen erforderlich, einschließlich der ausdrücklichen Einbeziehung einer Phase des Vertrauensaufbaus zwischen Forschern und Anwendenden; (ii) Rahmenbedingungen in Bezug auf Finanzierung, Normen und Vorschriften müssen systematisch bewertet werden, um festzustellen, ob und warum sie die Übernahme von Forschungsergebnissen erleichtern oder behindern könnten; (iii) Die vorhandenen Kapazitäten zur Erhöhung des Technology Readiness Levels müssen ausgebaut werden, z.B, durch die Bereitstellung von Finanzierungsprogrammen, die die langfristige Zusammenarbeit zwischen erfolgreichen Konsortien unterstützen; (iv) Es besteht Bedarf an europäischen und nationalen Diensten, die den langfristigen Zugang zu Forschungsergebnissen unterstützen; (v) Es müssen mehr Kapazitäten für die Aus- und Weiterbildung von Nutzenden bereitgestellt werden; (vi) Es besteht Bedarf an einer verbesserten sektorübergreifenden Anwendbarkeit durch die Harmonisierung von Methoden, Datenformaten und Terminologie; und (vii) Es ist ein Mechanismus erforderlich, um die Ausweitung bereits gut etablierter (aber potenziell sektorspezifischer) Forschungsergebnisse für kritische Infrastruktursysteme zu unterstützen.

Die Zielgruppen für diese Empfehlungen sind Finanzierungseinrichtungen, politische Entscheidungsträger und Normungsgremien, die die Rahmenbedingungen für die Forschung zur Resilienz von Infrastrukturen beeinflussen können, Koordinatoren von Forschungsprojekten und andere akademische/wissenschaftliche Einrichtungen, die oft die Hauptverantwortung für die Gestaltung von Forschungsprojekten tragen, sowie Praktiker, die (kritische) Infrastruktursysteme gestalten und verwalten.

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List of abbreviations

ACC-CG	CEN-CENELEC Coordination Group Adaptation to Climate Change (ACC-CG)
CEN	European Committee for Standardisation
CENELEC	European Committee for Electrotechnical Standardisation
CI	Critical Infrastructure
EACTDA	European Anti-Cybercrime Technology Development Association
EC	European Commission
ERNCIP	European Reference Network for Critical Infrastructure Protection
JRC	European Joint Research Centre
SoS	System of Systems
SRL	Societal Readiness Level
TRL	Technology Readiness Level
UBA	German Federal Environment Agency

1 Background and aim

Infrastructure is essential for everyday life; it is the backbone of vital societal functions as well as the social and economic well-being of people. It includes public and private assets, transportation, communication, electricity, and water networks, food production, waste treatment, industrial facilities, but also blue-green infrastructures that are vital for climate change mitigation and adaptation. With the acceleration of the climate crisis, climatic and other natural hazards have become one of the most relevant threats to infrastructure and the services it provides (European Commission 2021a): Heatwaves, droughts, wildfires, river and coastal floods, as well as windstorms, trigger disruptions in public transport, cause electricity blackouts, result in shutdowns of nuclear reactors, and numerous other impacts (European Commission 2021a; Forzieri et al. 2018; Forzieri et al. 2016). These impacts will rise rapidly in the coming years, especially in places already exposed to high temperatures and along coasts (cf. IPCC 2022, SPM-15, SPM.B.4.5), and are amplified by the increasing age of the European infrastructure stock (European Commission 2021a). Besides the direct impacts from fast-onset disasters (e.g., flash floods), the slow-onset stresses from climate change (e.g., sea level rise, long-term drought) can also significantly impact the capacity of infrastructure to respond and recover from other hazards and stressors.

Where the affected infrastructure is so vital to the maintenance of societal functions, health, safety, security, economic or social well-being that its disruption or destruction would have significant impact on a state and its ability to maintain these functions, it is labelled as **"critical infrastructure"** (CI) (Council of the European Union 2008). Over the last decades, this (critical) infrastructure has transformed from often isolated services or networks to interacting and interdependent parts in a highly connected **infrastructure "system of systems"** ("SoS", cf. Eusgeld et al. 2011). To acknowledge the full complexity of this SoS, it needs to be understood as a social-ecological-technical system (Chester et al. 2019; Grabowski et al. 2017): A complex bundle of system properties including physical and management structures and interdependencies, input and output resources, as well as technical and human capacities (Olfert et al. 2021).

The significant impacts from climate-related extreme weather events, as well as other ongoing and profound crises, such as the COVID-19 pandemic or the Russian-Ukrainian war, underpin the fundamental importance of the resilience of these infrastructure systems. With approaches of disaster risk management and climate change adaptation converging and climate-related extreme weather events becoming one focus of business continuity for infrastructure operators, it becomes even more important to put climate resilience into focus. **Climate resilience** addresses external stress factors related to climatically influenced natural hazards such as heat, drought, heavy precipitation, flooding, or windstorms. That is, it is the **capability of a system to prevent, withstand, recover from and adapt to threats imposed by hazards related to climate change.**

A new international working group is in the process of being set up, that will be supported by the German Federal Environment Agency (UBA) and the European Reference Network for Critical Infrastructure Protection (ERNCIP) in cooperation with the European Joint Research Centre (JRC), with the mission to **advance knowledge and practice on climate resilience** in infrastructure systems. To this end, it will bring together actors from practice, research, standardisation, and policy making from different national and EU-levels to discuss current issues of and develop recommendations as well as solutions for increasing the climate resilience of infrastructure systems.

In preparation of the new working group, UBA brought together an initial set of actors in the field of climate resilient infrastructures to start identifying critical subjects that would need to be addressed by the new working group. The initial discussions showed that there seem to be gaps in the science-policy-practice interface that prevent effective uptake of research outputs. As an analysis conducted by Lückerath et al. (2020) showed, numerous research projects produced various outputs to support infrastructure operators to advance climate resilience. However, these outputs usually remain at the level of isolated case-study application, often address only a limited number of relevant end-user needs, exhibit limited interoperability – both with existing and newly developed approaches –, and remain sector-specific. In effect, outputs often remain isolated 'research prototypes' which are not systematically taken up in practise to improve infrastructure resilience.

Therefore, the key questions were: What shortcomings of ongoing research on climate resilient infrastructure systems prevent a quick, systematic, effective, and visible uptake of research results? And how can these shortcomings be tackled by stakeholders from science, practice, and policy?

In this paper, we argue that a stronger focus on the uptake of research results into practice will require a closer look at how relevant research in the field of climate resilient infrastructure systems is incentivised, planned, designed, and performed at the interplay of science, practice and policy. Better designs and processes of knowledge exchange and collaborative knowledge production, as well as improvements to funding schemes and related regulations will propel cross-sectoral applicability and the scaling up of already well-functioning (but potentially sector-specific) methods and tools. It will thus support resilience-oriented action of decision-makers at EU policy level, European and national funding agencies, infrastructure operators, and standardisation bodies.

To address this issue, over the course of 2021, UBA commissioned a series of workshops and discussions with various experts – in addition to reviews of literature and EU project results. This paper presents the outcomes of this process. It **aims to identify infrastructure-specific factors that act as barriers** for successful transfer of research outputs into practice and **develop recommendations** for overcoming these barriers. To give actionable recommendations on how to make better use of research outputs in practice and subsequently enhance the climate resilience of infrastructure systems it identified success factors. The target audiences for these recommendations are funding bodies, policy makers, and standardisation bodies that can influence the framework conditions under which infrastructure resilience research takes place, research project coordinators and other academic/researcher institutions who are often the main responsible for the design of research projects, and practitioners who design and manage (critical) infrastructure systems.

2 The policy and standardisation landscape on climate resilient infrastructure

In view of the accelerating and emerging impacts from the climate crisis, there are clear European efforts on different fronts towards climate resilience. These focus on harmonisation and standardisation of concepts, methods, and tools to assess and manage climate resilience of infrastructure systems, as well as a on the redirection of funding and a convergence / streamlining of policy attention.

Within the **European Green Deal**, the European Commission (2019, cf. section 2.1.2) calls for a transition to climate neutrality via the use of smart infrastructure and acknowledges that *"existing infrastructure and assets* **will require upgrading** *to remain fit for purpose and climate resilient" and calls for "increased cross-border and regional cooperation"* in this context.

In its new **Adaptation Strategy** (European Commission, 2021b), the European Commission (EC) takes up this issue and calls for **more investments** in resilient, climate-proof infrastructure and acknowledges the need for climate proofing **guidelines specific to critical infrastructure**, which were published by the European Commission in 2021 (European Commission, 2021c). In its adaptation strategy, the EC also calls on Member States to include national standardisation in the implementation of their National Adaptation Strategies to speed up the standardisation of adaptation solutions. The new European Adaptation Strategy also calls for **harmonisation between approaches** of climate change adaptation and disaster risk management on national, EU, and international level (European Commission 2021b) to leverage synergies, which requires better standards, guidance, targets, resources, and knowledge.

This need for better guidance, knowledge, and collaboration also becomes apparent in the **Recommendations for National Risk Assessment for Disaster Risk Management in EU** (European Commission, Joint Research Centre 2021, p. 13). Those guidelines provide countries participating in the Union Civil Protection Mechanism with scientific support on how to conduct national risk assessments, how to use their results for disaster risk management planning, and how a **better collaboration between researchers, civil protection authorities, ministries, and other agencies** engaged in national risk assessments can be facilitated.

The increased need for collaboration is also acknowledged in the latest **overview of natural and man-made disaster risks the European Union may face** (European Commission 2021a), where the EC identifies seven priority areas for policy actions, of which two are relevant for the scope of this paper: *"(2)* **increasing cooperation across borders and sectors***, in all phases of risk management, to better address the transboundary nature of disaster risk, the increasing complexity and emergence of new threats;" and "(5)* **stepping up action** *to build resilience of critical infrastructure to intensifying natural hazards and man-made threats;". At the same time, the EC identifies that "Green infrastructure, green-grey hybrid infrastructure and nature-based solutions play an important role in mitigating weather-related disaster risks"* (European Commission 2021a, p.7).

An important infrastructure-specific initiative that mirrors the efforts in the other policy documents, is the EC's **proposal for a directive on the resilience of critical entities** (European Commission 2020). The proposal aims to reflect Member States' approaches to emphasise cross-sectoral and cross-border interdependencies and their increased use of *"***resilience thinking***, in which protection is but one element alongside risk prevention and* *mitigation, business continuity and recovery.*[1]*"* Specifically, the proposal acknowledges that *"[…]* **the current framework on critical infrastructure protection is not sufficient** *to address the current challenges to critical infrastructures and the entities that operate them"* and that *"[…] it is necessary to fundamentally switch the current approach from protecting specific assets towards* **reinforcing the resilience of the critical entities** *that operate them"* (section 1 of the explanatory memorandum to the proposal).

In parallel to the efforts of the European Commission, the European Committee for Standardisation (CEN) and the European Committee for Electrotechnical Standardisation (CENELEC) set up the **CEN-CENELEC Coordination Group Adaptation to Climate Change (ACC-CG)**[2] in 2014, which *"invites European Standardization Organizations to contribute to the European efforts aiming to make Europe more climate-resilient."* In CEN-CENELEC's Strategy 2030 (2021), the organisations underline the importance of adapting to climate change and the crucial role that standards can play here. The current plan of the EC to establish a high-level forum on the topic of climate change and standardisation with representatives of national standardisation organisations is another sign for the increasing momentum for harmonization.

In parallel to establishing the ACC-CG, numerous other standardisation activities on European and international level were initiated. Two technical committees develop standards on climate resilient infrastructures: **ISO/TC 268**[3] **Sustainable cities and communities** is focused on sustainability and resilient cities management (e.g., city representatives) while **ISO/TC 292**[4] **Security and resilience** is focusing more on safety and disaster management (e.g., first responders). A key technical committee for climate change adaptation standards is **ISO/TC 207/SC 7 Greenhouse gas management and related activities**, which covers mitigation and adaptation actions. These TCs are mirrored by the newly established **CEN/TC 467 Climate Change**, created in 2021.

Two of the most relevant results of the ongoing standardisation work are **ISO/TS 14092**[5] and **EN ISO 14091**[6]. ISO/TS 14092 is a standard for urban settlements that presents guidance for local governments and communities on how to prepare for climate change related threats and risks (pre-disaster). The EN ISO 14091 standard provides guidance to assess risks from climate change impacts and to understand climate vulnerability. It can be used as a framework for the assessment of climate change related risks in systems and organisations of any size (including infrastructure systems) as a basis for the planning, implementation, monitoring, and evaluation of climate change adaptation measures.

The increased need for climate resilience of infrastructure systems and calls to action on more harmonization, investments, and guidance is also taken up on national levels, as is exemplarily evidenced by the newly released **German Resilience Strategy** (German Ministry of Interior, 2022), which describes how Germany aims to implement the Sendai Framework for Disaster Risk Reduction. Not only promotes the strategy an all-hazards approach, including climate-related extreme weather events, but also calls for the establishment of a national hub for better collaboration across institutions – acknowledging that building resilience is a cross-cutting topic.

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[1] While the current wording of the directive proposal may not fully reflect the terminology used by the Disaster Risk Management community, it proposes a valuable translation to the term "resilience thinking" towards a broader view on social-technical systems.
[2] https://www.cencenelec.eu/areas-of-work/cen-cenelec-topics/environment-and-sustainability/climate-change/
[3] https://www.iso.org/committee/656906.html
[4] https://www.iso.org/committee/5259148.html
[5] https://www.iso.org/standard/68509.html?browse=tc
[6] https://www.iso.org/standard/68508.html

It needs more guidance and training for all involved actors, as well as increased research on the topic of resilient critical infrastructure systems.

These clear trends towards harmonisation and standardisation of concepts, methods, and tools to assess and manage climate resilience of infrastructure systems, as well as the redirection of funding are also apparent in **Horizon Europe**, the new EU programme for research and innovation. To support the EU's commitment to become climate-neutral by 2050, a minimum of 35% of the available funding will be directed to climate objectives, including resilient infrastructure systems. All four key strategic orientations in Horizon Europe cover impact areas that depend on critical infrastructure systems. These impact areas include: (i) (cyber)secure digital technology, (ii) more sustainable food systems, (iii) climate change mitigation and adaptation, (iv) smart and sustainable transport, and (v) preparing the EU against emerging threats by enhancing its disaster resilience. With Horizon Europe the EC also acknowledges the need to **focus on the uptake of research results**, moving to an impact-driven approach for proposal design, where the road towards impact and uptake will be a central focus of all proposals.

3 Barriers and recommendations for an improved uptake of research outputs

As the previous section showed, there is a need for harmonised concepts, methods, and tools to assess and manage climate resilience of infrastructure systems. More harmonisation would make it easier to provide guidance for increasing infrastructure resilience and subsequently allow to better steer financial investments towards increased infrastructure resilience. Research projects on resilient infrastructure systems from the past two decades have proposed manifold solutions. And while these solutions seem to be slowly converging, due to a continuously improving knowledge base and better cooperation formats between research and practice (including transdisciplinary collaboration formats and forms of real co-creation), these outputs still regularly remain at the level of isolated 'research prototypes' that are not brought into wide practical use.

This lack of uptake of research outputs is – at least partially – related to barriers and shortcomings in the science-policy-practice interface, an issue not only relevant to climate resilient infrastructure systems research but more general debates of how research results can be transferred into policy and practice. As identified by Weichselgartner and Kasperson (2010), barriers in the science-policy-practice interface that limit uptake of research outputs can be (1) functional factors relating to divergent objectives, needs, scopes, and priorities; (2) social factors relating to cultural values, communication, understanding, and mistrust; and (3) structural factors relating to different institutional settings and standards. These factors can be further sub-divided to allow a more nuanced analysis and subsequently the formulation of more targeted recommendations based on a system of influencing factors deduced from work dedicated to sustainability transition of infrastructure systems (project TRAFIS, UBA, cf. Hölscher et al. 2020):

- **Socio-cultural factors**, like user behaviours, expectations, or political goals, that drive or hinder specific innovations by creating or resisting new demands and strengthening or de-legitimising existing management systems (Frantzeskaki et al. 2009; Geels et al. 2018; Wilson et al. 2018).
- **Incentives and regulations**, like laws, funding programmes, or subsidies that can support (e.g., funding, business models) or limit (e.g., prohibitions, financial disadvantages) innovations or management practices (Markard 2011; Kern et al. 2017).
- **Local technological factors** on the demand and supply side, like requirements from energy grids or for retrofitting buildings, that foster path-dependencies or lead to internal system stress that open up or close opportunities for change and uptake of novel research results (Geels 2002; Frantzeskaki et al. 2010).
- **Institutional factors**, like organisational or market structures, that can result in standardisation processes and the alignment or fragmentation of strategic planning processes as well as collaboration and funding streams (Geels 2002; Adil et al. 2016; Truffer et al. 2010).
- In addition, **societal meta-factors**, like climate change, societal discourses, or new technological developments, can influence how well research outputs can be transferred into practice. These factors constitute broader societal trends and events outside of the infrastructure system, which can only to a limited extent be influenced by the actors within the system (Frantzeskaki et al. 2009; Geels 2007; Markard 2011).

During the discussions with European experts within the workshops in preparation of the working group, as well as in follow-up conversations, socio-cultural factors, incentives and regulations, as well as institutional factors emerged as the main types of barriers perceived regarding lack of uptake for research outputs for climate resilient infrastructures. While societal meta-factors are also perceived as relevant barriers, the limited ability to influence these factors pushes them out of scope for this paper. Local technological factors on the other hand, were not perceived as particularly relevant barriers for infrastructure systems, which often are characterised by a high permeation of technologies, which in turn means that actors involved with infrastructure systems are often used to handle novel technologies.

As a result, the remainder of this section focuses on barriers and recommendations relating to (i) socio-cultural factors, (ii) incentives and regulations, and (iii) institutional factors that hinder uptake of research outputs for climate resilient infrastructure systems.

3.1 Barriers and recommendation related to trust-building and co-design (socio-cultural issues)

More and more European research projects involve actors from different backgrounds ranging from universities, knowledge institutes, grid operators, urban policy makers, or social movements. These actors collaborate by making use of different forms of knowledge co-production to tackle complex societal issues (Pahl-Wostl et al. 2013; Norström et al. 2020). This increased co-production of knowledge leads to a shift away from the linear idea of knowledge transfer (research to practitioners) to a more interactive approach (e.g. Norström et al. 2020) with collaborative research design and the creation of collaborative and actionable research outputs. However, co-production of knowledge makes **socio-cultural differences** between research and practice environments more visible and therefore requires due attention in the design and implementation of collaborative research. This is especially the case for research on infrastructure systems, where the applicability of agile approaches to co-production is limited: The experimentation with alternative processes and methods for design and management are not allowed to jeopardize security of supply. Practitioners are focused on stabilising existing performances. Strong legal frameworks and regulations limit the room for experimentation.

3.1.1 Collaboration and trust building between researchers and practitioners

Problem definitions, working cultures, and the understanding of worthwhile results can vary strongly between actors of infrastructure research and infrastructure providers. Subsequently, expectations in a research project regarding the level of interaction between researchers and practitioners and how the process for knowledge co-production should be designed can vary widely (Chapman et. al. 2018; Hölscher et al., 2021). At the extreme end of the spectrum, researchers or practitioners might misinterpret knowledge co-production as a one-way street where they only co-operate via data and information transfer. Reasons for such a misinterpretation might be a general lack of experience of true knowledge co-production on both sides: Researchers are not perceiving stakeholders as knowledgeable experts or only as 'testers' of final outputs. Practitioners are used to a 'consultancy' relationship, expecting polished outputs and subsequently finding scientific questions of researchers not practical enough (Weichselgartner & Kasperson 2010). In the highly technologized infrastructure research space (see also section 3.2) with often very formalised development processes, these issues can be even more pronounced. As a result, real knowledge co-production, which benefits resilient infrastructure development or operation, seldomly takes place. To address these issues, to ensure effective collaboration, and to engage in actual co-production of applicable outputs, it is necessary to build trust and mutual understanding between the actors involved in infrastructure research projects early in the project. While many publicly funded research projects run three to five years, which should give ample time to build trust and understanding, **project design often does not account for the need for such a dynamic trust-building process**. Neither do the evaluation criteria for proposals and projects of funding bodies. This has proven even more challenging in the last couple of years when projects were forced to work remotely because of the pandemic; in some consortia, the project partners had the opportunity to meet face to face only after almost two years.

The issue of **lacking collaboration with stakeholders** is even more critical during the writing process of the proposal. Practitioners are usually not incentivised for writing / participating in research grants and subsequently need to take time out of their routine workday to discuss research questions and provide information to researchers. The need for a trade-off between 'actual work' and 'grant preparation' – often paired with very tight writing schedules – usually means that practical cases for research projects, specific end-user needs, and envisaged products of the research work are not very well defined during the proposal writing processes. This issue is even more pronounced for infrastructure systems, where operators are usually tightly clamped-in within the daily work to ensure smooth system functioning – especially during critical moments, as during the Russian-Ukrainian war. This finally results in a **disconnect between research objectives and the practical need**, e.g., of the infrastructure operator. Usually there is limited option to correct this mismatch after funding has been granted and work is started.

Recommendations for collaboration and trust-building

The development of new partnerships and the operational integration of different technical languages, disciplines, (methodological) approaches, perspectives (scientific vs. practical) or work cultures requires mutual understanding, learning, time, and flexibility of participants. This should be acknowledged by all parties, researchers, infrastructure operators, and funding bodies when funding collaborative research projects.

PROJECT COORDINATORS (RESEARCHERS & PRACTITIONERS) should allocate extra time in project design for trust building and mutual learning. This applies particularly where science and practice collaborate with different perspectives on the project objective. The first phase of a project (often the first year) should be considered as the 'finding phase' with detailed exchanges of needs and possibilities between different project partners to flesh out the initial work plan from the original proposal. This should be supported by moderated working groups, internal milestones, and time for testing working approaches.

FUNDING BODIES should follow a double strategy:

a) Explicitly acknowledge the trust-building need in call texts and require allocation of sufficient time and resources for this process in project design. This could include a requirement for a coordination task for partner interactions that deals with trust building processes, work plan adaptations, and other connected actions. As tasks of dissemination are already inherent part of research activities, these trust-building tasks must be added explicitly as well.

b) Extending the practice of follow-up projects for particularly successful partner constellations to make optimal use of accomplished trust building and learning processes. This could be achieved via a specific funding scheme that splits longer funding periods in two or more sections, where follow-up sections only require formal applications instead of completely new proposals (Example: Zukunftsstadt Initiative, BMBF, Germany). This would also allow to include a more explicit transfer period for research outputs. This could drastically improve the reachable Technology Readiness

Level of the output and the ease of uptake for research outputs taking into account the Societal Readiness Level (see below).

3.1.2 Cross-domain collaboration and large-scale co-creation

Research projects that target the complex topic of climate resilient infrastructure can suffer even more from a lack of practical collaboration, because they not only **depend on the collaboration with practitioners from individual infrastructure sectors**. The **need for transboundary collaboration of infrastructure operators and other key stakeholders distributed across different (neighbouring) countries**, is an important topic not only for telecommunication and transport infrastructure, but more and more also relevant for other sectors (e.g. health and critical ecosystems at / across country boarders). Besides the issue of cross-sectoral and cross-border collaboration, the limited personnel and time resources available in research projects makes large-scale inclusion of stakeholders an issue that is hard to tackle.

The complexity of resilience management of infrastructure also stems from the need to consider multiple hazards and cascading effects, which in turn requires **management of stakeholder groups from varying knowledge domains, who usually do not interact with each other** (natural risk and technology risk community, operators, civil protection ministries, environment, or labour ministries). This cross-domain collaboration often suffers from a lack of knowledge brokerage: **information (e.g., about climate-driven hazards) provided by experts from one field is often not made available in a form digestible and usable for other partners**, who might come from a different knowledge background, might not have any knowhow related to the topic at hand, and generally use different vocabularies. In the worst case, **lack of experience and knowledge might result in stakeholders not acting upon available information, leasing to disastrous outcomes** (Krausmann & Necci 2021).

Recommendations for cross-domain collaboration and large-scale co-creation

PROJECT COORDINATORS (researchers & practitioners) should put a focus on the need for knowledge brokerage when designing different forms of co-production. This can include: (i) providing time and opportunity for information exchange between partners with different backgrounds, (ii) producing target-group specific information formats, or (iii) including partners with specific expertise in knowledge brokerage.

FUNDING BODIES as well as **ACADEMIC / RESEARCH INSTITUTIONS** should incentivise societal impact of research even more. The Horizon Results Booster of the European Commission is a step in this direction. However, it is currently mostly focused on communication, dissemination, and exploitation of research outputs. It would be beneficial to extend the Horizon Results Booster to support also highly interdisciplinary research projects in how to translate complex research outputs into digestible and useable forms for experts from other fields.

When designing exchange and co-creation events with multiple practitioners, it is helpful to abstract from the specific infrastructure systems and / or disaster events under consideration. Starting out with discussing ‘hypothetical examples’ at the beginning of exchange and co-creation events can be an avenue to discuss more realistic events in a trusted environment later. For example, cross-border and cross-domain collaboration often improves when ‘extreme events’ that are seen as ‘unrealistic’ and ‘out-of-hands’ of the practitioners are discussed as these put everybody on a level playing field and prompts open discussion.

To facilitate wider participation from different governance levels, a combination of top-down and bottom-up collaboration approaches should be employed. While top-down approaches make use of clear roles and responsibilities, bottom-up approaches generate more acceptance. However, bottom-up approaches require larger flexibility and the ability to tolerate a higher level of ambiguity. An example of where the top-down approach works well is the UP KRITIS initiative in Germany. Here, heads of Critical Infrastructure operators cooperate and transfer the gained knowledge into their institutions. The network is meant to facilitate trust-building and sharing of examples across sectors and works quite well, but the lessons learned from UP KRITIS meetings take some time to trickle down into day-to-day work. Bottom-up approaches on the other hand, involve actors from different organizational levels and can result in quicker uptake across institutions. An approach that involves heads of infrastructure operators as 'champions of change' as well as actors from the more operational levels as 'knowledge brokers' seems particularly useful for infrastructure systems.

3.2 Barriers and recommendation related to incentives and regulations

The socio-cultural barriers identified in section 3.1 are linked with and can be reinforced by barriers related to **incentives and regulations**. On the one hand, incentives for researchers and practitioners differ widely, with reward systems for researchers often being linked to (long-term) scientific excellence (Weichselgartner & Kasperson 2010), while reward systems for practitioners usually being linked to compliance with service-level agreements or (short-term) profit. On the other hand, regulations, legal frameworks (e.g., on data exchange and the presence of classified information), as well as research programmes and funding schemes designed by policy makers can influence how researchers and practitioners interact with each other, what kind of research outputs are produced, and which capacities (personnel, time, money) are made available. This in turn can influence the quality of research outputs. Infrastructure research programmes on European level increasingly cover broader topics and require a higher degree of multidisciplinarity, and thus higher complexity (see also section 3.1). Because current European research programmes also limit the number of funded projects further compared to previous programmes, successful research projects often have to promise more and increasingly complex results under limited budgetary capacities of individual partners. This can in turn limit the intensity of interactions, the agility of the knowledge co-production process and the stakeholder engagement processes, subsequently influencing the quality of outputs.

3.2.1 Using standards and regulations to design research and collaboration

While research programmes focus more and more on trans-disciplinary approaches to resilience and sustainability, national and European transformation strategies often focus on economic and technological aspects of resilience, only addressing the societal dimension to a limited degree (see also section 2). For example, when targeting local, individual, and just resilience the new European Adaptation Strategy focuses on financing, the use of digital technologies, the involvement of regional bodies, and on economic adaptation (e.g., via re-skilling of workers). It does not fully address the necessary societal transformations that go beyond the economic dimension (European Commission, 2019; cf. section 2.2.2). This in turn might incentivise practitioners and researchers to focus more on 'hard' economic-technical solutions to infrastructure resilience and limit the development and use of 'soft' societal solutions. A strategic focus on economic-technical solutions might also result in a limited take-up of societal solutions. This limits also their potential for increasing infrastructure resilience. These effects can be reinforced by the longevity of infrastructure systems and strict regulations of the infrastructure sector, which often favours technology-focused solutions and top-down approaches.

Another example where strategic incentives influence research output is presented by Bogner and Dahlke (2022), who analysed the German Bioeconomy Strategies and connected research projects: *"The analysed strategies and the resulting projects feature a dominant focus on the techno economic dimension [...], which is represented by reoccurring themes around competitiveness, technology, eco-efficiency, innovation, economic output, [and] industrial applications." This results in the "produc[tion of] top-down technological solutions [rather] than engaging in participatory problem framing or solution finding"* (Bogner & Dahlke 2022, p.9).

Notably, the new German Resilience Strategy (German Ministry of Interior, 2022) and the EC's proposal for a directive on the resilience of critical entities (European Commission 2020) acknowledge the need to take a more holistic perspective and take a step in incentivising a more social-ecological-technical systems perspective on infrastructure systems.

Recommendations for harmonizing objectives of research with societal requirements for transformation

POLICY MAKERS as well as the **RESEARCHERS AND PRACTITIONERS** in strategy development need to be more aware on how the focus of policy and research-policy strategies can influence the design of research projects. This includes which outputs are produced, and subsequently how well research outputs can be taken-up in practice. It is advisable to review existing strategies and policies regarding the incentives they provide to researchers and practitioners. A shifting focus from the economic-technological perspective to an integrated perspective of the social-ecological-technical infrastructure system is necessary.

At the same time, **FUNDING BODIES** should make sure that the necessarily highly transdisciplinary research projects that require large consortia receive sufficient funding (for all partners). They should also provide more targeted research programs. The temptation for project consortia to over-promise due to high competitiveness and an unrealistic amount of expected project outcomes should be reduced. This however should not prohibit **FUNDING BODIES** to require research projects to *"incorporate more heterogeneous actors to foster inter- and transdisciplinary knowledge co-creation. These actors may need to be different in age, gender, social and educational background in order to allow for different solution options and overcome paradigmatic "lock-in" in unsustainable value systems as well as the issue of bounded morality of systemic actors*" (Bogner & Dahlke 2022, p. 9).

3.2.2 Using standards and regulations to drive take-up of research outputs

While incentives and regulations can influence the design of research projects and how researchers and practitioners interact (i.e., the 'upstream' part of the science-policy-practice interface), they can also directly trigger changes and improvements to the design and operation of infrastructure systems (i.e., the 'downstream' part of the science-policy-practice interface). Subsequently, conceptual frameworks (e.g., idealistic models on how the resilience management process for infrastructure systems can work) and associated guidelines, standards, and regulations should be used as an avenue to incentivise uptake of research outputs.

As shown in section 2, efforts that support this top-down approach are already taking place in the areas of sustainable cities and communities (e.g., ISO/TC 268), disaster risk management for first responders, urban settlements, and environmental management systems. Other examples of such efforts are the Seveso, ECI and NIS Directives. However, like the results of the top-down approach for collaboration (see section 3.1), it takes time until standards and frameworks are put into application; even more so, considering that sector-specific guidance and practices are also very much needed (one size does not fit all). To support quicker adoption of new standards, regulations, and framework – and subsequently drive more uptake of research outputs, bottom-up approaches (e.g., via living labs), to get more acceptance from a larger number of stakeholders, as well as for test and validation of novel research outputs should be employed.

Recommendations to support standardisation and regulations for take-up of research outputs

POLICY MAKERS, PRACTITIONERS, AND RESEARCHERS should systematically evaluate currently adopted standards, regulations, and frameworks to identify if and why they might facilitate or prohibit the uptake of research outputs, e.g., because they do not handle infrastructure systems as social-ecological-technical systems (see also previous recommendations). This analysis should be conducted in cooperation with sector-specific associations (e.g., GIE, ENTSOG, ENTSOE), the Critical Entities Resilience Group (The European Commission, 2020), and reference networks (e.g., the ERNCIP Project) to also enable discussions on cross-border and cross-sectoral issues.

European and international **STANDARDISATION BODIES** should:

a) develop standards, guidance, and frameworks aiming at a holistic approach for climate resilience that covers the social-ecological-technical dimensions of infrastructure systems;

b) along with cross-sectoral standards, foster the development of sector-specific standards to address the operating condition of specific sectors or sub-sectors of infrastructure systems;

c) every time condition b) applies, examine if measures emerging from the sector-specific standards can be transferred to existing cross-sectoral standards. This could simplify and speeds up the cross-sectoral adoption of measures.

3.2.3 Compliance with regulations and data protection

While there is an increasing level of harmonization for regulations and legislation on European level (e.g., GDRP, CER directive), there still exist differences on national level and below, especially regarding infrastructure systems, but also regarding resilience topics like climate change adaptation and disaster risk management. With the limited capacity often available for research projects (see previous section) research outputs are often not compliant to all relevant **regulations and standards** on the European, national, regional, and local levels, because researchers might focus on specific aspects or a selected number of countries. This issue is especially critical for cross-border infrastructure systems, where not only different regulations, but also different approaches to handle different types of risks might come into play.

Some of these issues are reinforced by the social-cultural barriers identified in section 3.1, which can result in **priorities and requirements** (e.g., from regulations) of practitioners not being clear and / or not being shared with the research organisations and are therefore not considered in the design of the methods or tools.

The criticality of infrastructure systems for the functioning of society means that their resilience is inevitably linked to security sensitive questions. This relates to questions of **data protection**, which can limit access and exchange of relevant data and knowledge, but also publication of research outputs. Subsequently, without information about which data is available where and in which format, research can result in outputs that are only applicable for a limited number of cases for which this information is available.

Recommendations for compliance with regulations and data protection

The increased calls for more harmonization of concepts and approaches, as well as regulations (see also section 2) by **POLICY MAKERS** are a step in the right direction to address issues of limited compliance of research outputs with regulations on European, national, regional, or local level. However, the European harmonization initiatives need to be translated into suitable national legislation, reflecting the national specifics. The German Resilience Strategy (German Ministry of Interior, 2022) is a good example, which translates the Sendai Framework into a national strategy that further needs to be broken down into regional implementation plans.

RESEARCHER AND PRACTITIONERS on the other hand should use combined top-down and bottom-up collaboration approaches to achieve wider participation and subsequently identify policies and priorities of relevant stakeholders (see also section 3.1).

Data protection on the other hand should not be seen as a barrier, but rather as a valid 'protective barrier' to avoid security incidents and protect critical information. However, it is still necessary for researchers to get a hold of relevant data to produce useable outputs. To overcome the issue of lack in data **PRACTITIONERS, POLICY MAKERS, RESEARCHERS, AND STANDARDISATION BODIES** should follow a dual strategy:

a) They should define a unified data model for information on critical infrastructure systems, hazards, impacts, and vulnerabilities. The INSPIRE Directive – which the EC plans to revise soon – could be a starting point for such a model.

b) They should jointly define and make available to the research community artificial data sets that define 'benchmark scenarios' on which research outputs can be developed.

To develop applicable research outputs, it is not necessary to directly employ data from critical infrastructure providers. However, it is necessary to have access to data that is sufficiently close to real-world data. This requires common models and artificial scenario data.

3.2.4 Technology Readiness Levels

The ability of research projects to produce results with a high enough Technology Readiness Level[7] (TRL) can be a limiting factor for uptake of research outputs. For immediate use by practitioners or uptake in standardisation, research outputs need to achieve a high enough maturity level. This is especially relevant for infrastructure systems as the backbone of critical societal functions. However, many scientific innovations take place on the lower TRL and still provide important new early insights for practitioners. Where research projects cannot produce a TRL high enough for immediate uptake in practise or standardisation, outputs need to be made available in a way that allows easy understanding by practitioners and / or uptake (e.g., by follow-up projects) to increase their TRL afterwards.

However, an exclusive focus on the Technology Readiness Level for assessing the maturity of research outputs might incentivise a too narrow technological focus (see also introduction to section 3.2), ignoring the social-ecological aspects of infrastructure systems. Here, new approaches like the **Societal Readiness Level[8] (SRL)**, that not only assess the maturity of technology itself, but also include the acceptance of stakeholders and society, can be a good approach.

[7] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf
[8] https://newhorizon.eu/societal-readiness-level-thinking-tool/
https://innovationsfonden.dk/sites/default/files/2019-03/societal_readiness_levels_-_srl.pdf

Recommendations for Technology Readiness Levels

FUNDING BODIES should take a three-pronged approach to address the TRL barrier:

a) Explore ways to allow for longer-term collaboration over families of projects, allowing consortia to take promising research outputs to higher TRLs (see also recommendations on trust building). This could also be facilitated via dedicated initiatives and association, like the European Anti-Cybercrime Technology Development Association[9] (EACTDA).

b) For fundamental research or where projects cannot reach a TRL sufficiently high for uptake in practice or standardization, support for long-term provision of these research results after the project ends should be provided (see also recommendations on institutional factors).

c) The usability and soundness of the SRL should be further explored to shift the focus away from the narrow technology aspect to a holistic social-ecological-technical system understanding of infrastructure systems.

3.3 Barriers and recommendations related to institutional factors

The main institutional barrier for uptake of research outputs regarding climate resilient infrastructure is the disconnection of planning horizons and planning dynamics between researchers, practitioners, and policy makers. Even though infrastructure systems must remain functional, durable, and safe over a long time, and should thus favour investments with longer return-on-investment, there still seems to exist a prevalence of **short-term cost-benefit-calculations** by infrastructure operators (Hölscher et al., 2020). Researchers on the other hand usually take the perspective that **resilience requires long-term thinking and preparation**. This again results in a mismatch of expectations in context of the project outcome as practitioners often call for specific action-steps that can be implemented immediately, while researchers call for keeping the long-term resilience perspective in mind, even while developing outputs for short-term action.

Another institutional barrier that hinders uptake of research outputs is a **lack of easy and long-term accessibility to research outputs for both practitioners as well as researchers**. As the project funding ends when the final deliverables are produced, after the project conclusion, research outputs are often not stored and provided in a way that enables easy uptake by follow-up projects (from different consortia). Subsequently, if research outputs are not immediately taken-up by an organisation or maintained by their producer over a longer time span, they quickly become obscure, inaccessible, and unusable for other parties after the end of a project. This in turn can result in research projects unintentionally 're-inventing the wheel', lowering the efficiency of research funding or other investments in climate resilience.

Connected to this issue is also a **lack of targeted information and training** on research outputs. This concerns both the usage of research outputs (e.g., manuals, online trainings) and the opportunities for life-long learning (e.g., via materials and courses on resilience management).

Recommendations for institutional factors

FUNDING BODIES should employ a double strategy to address the identified barriers:

a) Provide and advertise a service and platform for (open access) storage of research outputs. This not only includes publications and deliverables but also software, handbooks, datasets, and other

[9] https://www.eactda.eu/

research outputs. A good example for keeping achieved research outputs available is provided by EISAC.it[10] – the European Infrastructure Simulation and Analysis Centre, which was initiated via the CIPRNet project and has the aim to build up national nodes that support Operators and Public Authorities in better protecting Critical Infrastructure and in enhancing their resilience by providing access to research outputs and expertise. Unfortunately, until now only the Italian node was able to commence operation and the European association was now shut down for a lack of funding. The European Anti-Cybercrime Technology Development Association[11] (EACTDA) is another good example of how to foster further development of research outputs with the aim to increase uptake. For scientific publications, the new Open Research Europe platform[12] is a step in the right direction, providing easy and fast open access publication opportunities. Such a platform for storage of research outputs related to climate resilient infrastructure systems – and potentially other European research outputs – would allow to focus investments.

b) Mandate (and provide funding for) medium-term operation and maintenance of research outputs by the producing organisations as well as making research results accessible to follow-up projects, if they are not being exploited by the original producers. This would require the provision of specific funds, standardised data, and accompanying documents as part of each product-oriented research project.

This process should be supported by a 'cold case task force' group of researchers, practitioners, and other actors that track down promising research outputs that are not maintained anymore to study them and try to make them accessible again.

In conjunction with these requirements, it is necessary to provide specific training opportunities to increase guidance for infrastructure operators and other related stakeholders on climate resilience for infrastructures – not just once at the end of a project but as a permanent option. There is a need for life-long-learning opportunities and increased guidance to support system-changes (when it is about transformation). This includes the use or implementation of research results or the use of available public data, e.g., from Copernicus. To realise this, a new role definition of **RESEARCHERS**, active openness of **PRACTITIONERS**, and a funding basis provided, e.g., by **FUNDING BODIES**, is required. An increase in training opportunities would also support the calls for more guidance on climate resilient infrastructures found in policies and strategies on European and national level, as identified in section 2. These training opportunities should not just focus on applying research outputs, but also cover other topics with specific relevance for infrastructure resilience, like cross-border cooperation, investments in climate resilience, and a general shift to resilience thinking.

[10] http://www.eisac.it/
[11] https://www.eactda.eu/
[12] https://open-research-europe.ec.europa.eu/

4 Concluding remarks

The barriers and recommendations in this paper throw a light on climate resilience in infrastructure systems. Key lessons for facilitating climate resilience of infrastructure systems are the need for

- a better approach to knowledge co-production during all phases of research,
- improvements to framework conditions regarding funding, standards, and regulations,
- more capacity to raise Technical Readiness Level considering Social Readiness Level,
- more services to provide long-term access to research outputs,
- increased capacity for training and education,
- improved cross-sectoral applicability, and
- scaling up of already well-functioning (but potentially sector specific) research outputs.

While the focus of the recommendations in this paper is on (critical) infrastructure systems, and specifically infrastructure understood as social-ecological-technical systems, several recommendations are generally applicable for improving the take-up of research outputs.

Based on the results presented in this paper, the upcoming working group on climate resilience under ERNCIP will identify specific issues to examine in more details. For example, it seems worthwhile to analyse selected guidelines and regulations (e.g., the Technical Guidance on Climate-proofing Infrastructures (European Commission, 2021c)) regarding their support for improving the climate resilience of infrastructure systems, and to develop recommendations for improving these guidelines.

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