🏆 *reviewed paper*

Awareness about the Relevance of Cascading Effects in Urban Critical Infrastructure Networks under Climate Change – a Participatory Impact Matrix Approach

Markus Groth, Steffen Bender, Peer Seipold, Elisabeth Viktor

(Dr. Markus Groth, Climate Service Center Germany (GERICS) - Helmholtz-Zentrum Hereon, Markus.Groth@hereon.de)
(Apl.-Prof. Dr. Steffen Bender, Climate Service Center Germany (GERICS) - Helmholtz-Zentrum Hereon)
(Dr. Peer Seipold, Climate Service Center Germany (GERICS) - Helmholtz-Zentrum Hereon)
(Elisabeth Viktor, PricewaterhouseCoopers GmbH (pwc))

1 ABSTRACT

Addressing climate change adaptation in urban areas is increasingly urgent. To achieve sustainable and climate-adapted fields of action requires fundamental transformations of supply chains and infrastructures such as transport and mobility, electricity and water supply, or telecommunication as well as an improved understanding of their interactions. Practical experiences show, that in general there is an increasing awareness about this, but for example emergency plans or crisis communication often falls short regarding the indirect impacts of climate change on potential infrastructural failures. Hence, there is also a growing need for applied research and systemic approaches to overcome the current prevailing isolated sectoral view of climate change impacts to gain a holistic understanding of the critical infrastructure networks. Against this background, the paper highlights the relevance of climate change impacts on critical infrastructures, infrastructure interdependencies and potential systemic cascading effects. The analysis uses a participatory approach that has been applied within a case-study for the metropolitan area of Hamburg, Germany. It is based on transdisciplinary research methods, connecting the realms of scientific knowledge about regional climate change with real-world experiences. A strong focus lies on the use of a specific impact matrix approach carried out with key stakeholders from different sectors to identify climate-related drivers causing the most severe failures and losses in the system – either directly in the same sector or indirectly due to breakdowns in other sectors. In sum, the case-study enables a first categorization of the role single key variables play in the infrastructure system. Furthermore, it introduces the topic of adaptation to climate change as a starting point for a better understanding and management of systemic risks in order to build and maintain resilient critical infrastructures and to make urban areas safe, resilient and sustainable.

Keywords: transdisciplinarity, impact matrix, urban areas, critical infrastructure, climate change adaptation

2 INTRODUCTION

Addressing climate change adaptation in cities and urban areas is increasingly urgent as for example nearly 75% of Europeans live in urban areas. This number is expected to grow in the coming years. Moreover, the way cities are planned and constructed often remains unsustainable, like for example the EEA (EEA 2020) points out. The report also highlights, that while many local authorities have realised the importance of becoming resilient to climate change, progress in adaptation planning remains small, whereas the implementation of adaptation measures and the monitoring of their success are even smaller. Measures currently put in place mostly focus on redressing grievances, developing knowledge, awareness raising or policy developments. Technical adaptation solutions have not yet been implemented equally across Europe. At the same time, adaptation of cities is also necessary from an economic perspective. Urban areas are key economic hubs and home of industry and services. Therefore action at all governance levels from EU through national to local is needed to support urban adaptation through improved access to knowledge and funding, political commitment and community engagement, and mainstreaming adaptation into all policy areas (EEA 2020).

This is strongly in line with results from the IPCC special report "Global Warming of 1.5°C". It highlights urgent need for action and shows that even a warming of 1.5°C compared to pre-industrial levels will lead to locally strong impacts of climate change. The overall economic damage up to 2100 can be regionally higher if global warming does not reach 1.5°C but 2°C. In turn, all emission paths for the target of 1.5°C or below require rapid and far-reaching emission reductions as well as system transitions in many socially and economically significant areas. Thereby urban areas are one type of the critical systems that can accelerate and upscale climate action, including both mitigation and adaptation (IPCC 2018). This requires fundamental transformations of central critical infrastructures such as electricity and heat supply, water supply, sewage disposal, transport and mobility or telecommunication as well as an improved understanding and comprehensive consideration of the interactions between critical infrastructure sectors under changing climatic conditions – also taking into account the urban-rural-relations (European Commission 2020a; EEA 2019).

Since the different supply networks are interconnected and dependent on each other, it is mandatory to analyse climate-related concerns with a clear perspective on the entire infrastructure system, including direct and indirect impacts (European Commission 2020a; EEA 2019; Laugé et al. 2014; Eusgeld et al. 2011; Luiijf et al. 2010; BMI 2009; Rinaldi 2001). For instance, if the power supply fails due to extreme weather conditions, serious consequences can follow relating to a number of vital functions in a region (Forzieri et al. 2018; Groth et al. 2018; Mikellidou et al. 2018; Karagiannis et al. 2017): The supply of fresh water can be disrupted, water quality can be compromised and wastewater treatment can be affected. The transportation system can be disturbed, leading to potential failures of evacuation measures. The telecommunication system can break down leading to a halt in transport, mobility and logistics, to name a few examples. In addition, critical infrastructures contain fewer and fewer mechanical redundancies and rely more and more on smart networks and digital information exchange, creating an accumulation of risk and exposing the system to a number of threats.

The exchange of experience with local stakeholders shows, that in general there is an awareness of these interconnections, but for example emergency exercises often fall short regarding the growing indirect impacts of climate change on potential infrastructural failures in the future. Therefore, there is a growing need for practice-oriented research to overcome the still dominating isolated view of single impacts of climate change on selected critical infrastructures (EEA 2020; European Commission 2020a; Lückerath et al. 2020; Groth et al. 2018). An additional challenge is the consideration of the large number of interests from key players such as administration (from local to regional), politics, and companies as well as state of the art scientific knowledge to be considered in the development of strategies and measures.

Against this background, the paper addresses general aspects of the relevance of climate change impacts for critical infrastructures, infrastructure interdependencies and potential cascading effects as well as takes a hands-on deep dive into the topic by introducing the methodology and main results of a case study carried-out with stakeholders in the metropolitan area of Hamburg.

The paper is structured as follows. Section three highlights the overall relevance and need for research regarding the impacts of climate change on critical infrastructure, with a focus on infrastructure interdependencies and cascading effects. The case-study background is described in section four. Based upon this, section five introduces the specific impact matrix approach used as part of a stakeholder workshop within the case-study. The main results are presented and discussed in section six. The paper concludes in section seven.

3 CRITICAL INFRASTRUCTURE, INFRASTRUCTURE INTERDEPENDENCIES AND CASCADING EFFECTS

Critical infrastructures are defined as organisations and facilities of great importance to the state, whereby their failure or impairment would result in serious supply shortages, considerable disruption of public safety, or other dramatic consequences (BBK and BSI 2020).

In this paper, the focus is put on three elements: energy, water and transportation. The aim is to identify the connections and interactions between these sectors and to analyse the underlying dynamics. In doing so, possible weak links and vulnerabilities, leading to cascading effects, can be identified. Specifically with regard to the impact of extreme weather conditions also leverage points for the most effective implementation of adaptation options can be determined. This information forms the basis for the objective to strengthen the resilience of all parts of the critical infrastructure and to reduce vulnerability and risk regarding climate change impacts in the future.

Regarding the specific impacts of climate change in Germany – for instance – the transport and mobility infrastructure are particular expected to be affected by extreme weather events (Hänsel et al. 2019; Nilson et al. 2019). Damages and obstacles caused by floods and landslides – for example – are key challenges for road and rail transport. The navigability of waterways can be impaired especially by exceptionally high or low water levels or by trees falling and blocking the fairway. In addition, especially in combination with strong winds and heavy precipitation, damage can occur to infrastructure elements such as traffic control systems, overhead lines and power supply systems, as well as inland waterways, ports and maritime facilities. Disturbances of the transport system can cause disruptions in other economic sectors (e.g. producing industry, chemical and pharmaceutical industry) and thus also in other infrastructure services, as observed for example during the period of low water levels in the River Rhine in 2018. Due to low water levels and high water temperatures, there was a lack of cooling water for thermal power plants, which had to be partially throttled. At the same time, the logistics chain for the supply of iron ore, coal and crude oil as well as for the delivery of end products from steel works and the chemical industry on the Upper Rhine was hampered. This resulted in supply bottlenecks for diesel and gasoline (BfG 2019).

Dependencies of critical infrastructure elements in general have already become a growing phenomenon in practice (Lugo 2019; Johansson et al. 2015; Ciscar and Dowling 2014; Moss 2014; Funabashi and Kitazawa 2012; Frantzeskaki and Loorbach 2010; Meusel and Kirch 2005; Rinaldi et al. 2001). The main types of failures describing these interdependencies are i) cascading (manifestation of nth-order-effects), ii) escalating (disruption in one infrastructure causes a larger disruption for another infrastructure) and iii) common cause (disruption in several infrastructures at the same time, e.g. due to geographical interdependencies). In particular, a cascading effect occurs when a disruption in one infrastructure causes the failure of a component in a second infrastructure, which subsequently causes a disruption there, too (Hassel et al. 2014; Rinaldi et al. 2002). In general, critical infrastructure is exposed to various kinds of threats. They are man-made or technical (terrorism, sabotage, software failures etc.) and natural threats. The latter range from geological (landslides, earthquakes etc.) to hydro-meteorological hazards (extreme weather events). Their effects generate a sequence of events in human subsystems that result in physical, social and/or economic disruption. Thus, an initial impact can trigger other incidents that lead to consequences of significant magnitude.

In the EU-project CascEff (Hassel et al., 2014), it is also pointed out, that data collection based on interviews, would be beneficial to analyse these potential system failures, because information about the effects of the conditions under which cascading effects occur is very hard to find. Hassel et al. (2014) therefore suggest holding workshops using contrafactual reasoning (“What if…?” scenarios). This suggestion is taken up in the case-study presented below. Thereby especially physical interdependencies are taken into account, which – if stressed or disrupted – can cause cascading failures for any type of infrastructure, which can lead to safety and security threats or can severely harm economic opportunities and society.

4 CASE-STUDY BACKGROUND

Studying complex systems like critical urban infrastructures means analysing “how parts of a system and their relationships give rise to the collective behaviours of the system, and how the system interrelates with its environment” (Bar-Yam 2002). The crucial determinant of a complex system is its purpose. This is essential to understand the behaviour of the system and to identify influencing factors and leverage points to intervene. A complex system in general is made of stocks, flows and feedback loops. Since a system to a large extent causes its own behaviour, it is helpful to understand which features in the system are the most dominant drivers. How to identify leverage points (active variables) to interfere in the system are described in Meadows (2008).

Against this background, the system dynamics approach helps to understand the non-linear behaviour of complex systems. It was developed by Jay W. Forrester in the 1950s (Forrester 2007a) as a heuristic method to analyse socio-economic systems. Originally, the method was applied to study the impacts of specific business decisions on the behaviour and structure of the business. It allows to go through different options/decisions (i.e. scenarios) and to compare the respective expected reaction of the business (the system) over time (Forrester 2007a; 2007b).

To systematically capture the complex interlinkages of different infrastructure sectors in practice and the impact of future climatic conditions for potential cascading effects, a system dynamics approach has been applied in a project for the metropolitan area of Hamburg. The system under investigation is built from the infrastructural elements of the energy, water and transport sectors. A special focus is placed on the interfaces between these sectors.

ISBN 978-3-9504945-1-8. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER

The project is based on transdisciplinary research methods, connecting the realms of scientific knowledge about regional climate change with real-world experiences in sector management. Thereby transdisciplinary research is understood as a deeper and broader form of interdisciplinary research. It is deeper because it transcends disciplines and thereby blurs discipline boundaries. It is broader because it includes not just scientists, but also stakeholders such as citizens and authorities, who should ideally participate in all phases of the research process. Transdisciplinary research represents a unified problem-solving approach in which problems are tackled not only from a disciplinary perspective but grappled with in their entire complexity. Therefore, transdisciplinary research is necessary to solve problems that arise at the intersection of science and society or what is sometimes referred to as the "life-world".

In this context, a participatory approach is applied to identify climate-related drivers causing the most severe failures and losses in the system – either directly in a specific sector, or indirectly affecting a sector due to breakdowns in subsystems.

Starting with identifying key players and identifying the affected and affecting institutions, a stakeholder mapping process (Leventon et al. 2016; Reed et al. 2009) was carried out for the energy, water and transport sector. Based on this, 25 local representatives and experts of the most relevant groups have been contacted. Thereof 13 stakeholders have been interviewed regarding a) their expertise and perception about climate related risks, b) the most vulnerable elements and their dependence on non-climatic influences, especially from the failure of important elements of their own sector or connected sectors, c) their level of preparedness, and d) their institutions adaptive capacity. In a co-design process, cognitive maps were built representing the individual mental models of the interviewees and showing their perspectives of the current local system.

In a next step, connections between the generic terms were defined and combined in one map, based on group model building techniques (Siokou et al. 2014; Bérard 2010; Sterman 2001; Andersen and Richardson 1997; Vennix 1996). This highlights the most frequently mentioned variables of the system and their interlinkages from the stakeholders' perspective. Finally a stakeholder workshop has been carried out, whereby mainly elements of the sensitivity model developed by Vester (1991; 2003) have been applied. This specific approach will be described in more detail in the next chapter.

5 AN IMPACT MATRIX APPROACH AS PART OF A STAKEHOLDER WORKSHOP

One key element of the case-study was a join workshop with the previously already interviewed stakeholders. Thereby it was aimed at distilling those system variables that the stakeholders deemed most relevant, as well as on analysing the impacts these variables have on each other. The participants were split up in three groups for the discussion in order to learn about the individual assessments and to enable each participant to share his/her particular view. Additionally, the workshop provided a possibility for the participants to extend their own cross-sectoral network.

Careful consideration of the process of how to work on the problem at hand is important (Bérard 2010) for a successful workshop in this setting. Different types of cognitive tasks can be applied: i) divergent thinking, done in small groups or by individuals to broaden the space of possibilities to look at the problem (or potential solutions), ii) convergent thinking, often achieved in plenary discussions to concentrate the amount of possibilities to the ones that are deemed most relevant by the group, and iii) evaluation, also mostly done in a plenary setting to evaluate chosen possibilities.

Aside from the group model building techniques discussed in the system dynamics community (e.g. Andersen & Richardson 1997; Andersen et al. 1997, Vennix 1996), it was decided for the workshop to strongly focus on elements developed by Vester (1991; 2003) of working with complex systems.

The sensitivity model was developed to capture the behaviour of non-linear processes and complex systems (Vester 1991). Just like Forrester (2007a; 2007b) and Meadows (2008), Vester considers the understanding and accurate representation of feedback loops as essential. In addition, Vester offers a number of concrete tools that help to set boundary conditions and to prepare for the identification of feedback loops in a structured way (Vester 2003).

The set of variables to be used need to contain information about (Vester 2003):

- Direction of impact (x influencing y, or y influencing x)
- Desired direction of change (increase or decrease, impact of change)
    - Strength of relationship: 0 = No relationship; 1 = Weak relationship; 2 = Medium relationship, proportional; 3 = Strong relationship, disproportionate.

Thereby, it is important to only focus on direct relations. The indirect relations appear automatically when describing the entire system. Based on the variable's description, an impact matrix can be developed as illustrated in figure 1.

Impact of ↓ on →	Influencing factor A	Influencing factor B	Influencing factor C	Influencing factor D
Influencing factor A		1	1	...
Influencing factor B	2		...	2
Influencing factor C	...	0		...
Influencing factor D	3	...	...	

Impact Matrix = basis to define roles of individual influencing factors

Fig. 1: Illustration of the impact matrix (Vester 2003)

An impact index can be calculated with the impact matrix (figure 1) for each factor influencing the system, i.e. each variable. For doing so, the following approach is suggested. After all influencing factors have been evaluated in the impact matrix, the individual values are added row by row to form the active sum of the respective variable. By adding the values column by column, the passive sum of each variable is calculated (Vester 2008; 1991). The active sum allows a statement about how strongly the variables affect the system. Accordingly, the influencing factor with the largest active sum has the greatest influence on the system, whereby this is independent of whether the influencing factor is simultaneously influenced by others. In contrast, the passive sum allows a statement about the strength on how each variable is influenced by other variables in the system. Active and passive sums form the basis for the assignment of the influencing factors to different categories. For each influencing factor, its active sum could then be divided by its passive sum. The influencing factor with the highest quotient is an active variable in the system. Correspondingly, the variable with the smallest q-value is a reactive variable. In a next step, for each influencing factor its active sum is additionally multiplied by its passive sum. The lowest p-value identifies the buffering variable of the system.

Based on these values, each variable can be assigned one of the following five roles in the system (Vester 2003):

- Active: large influence on other variables without being influenced by other variables
- Reactive: small influence on other variables, being influenced strongly by other variables
- Critical: large influence on other variables, being influenced strongly by other variables
- Buffering: small influence on other variables without being influenced by other variables
- Neutral: work well to self-regulate the system.

6 RESULTS

The initial representation based on the interviews already allows certain insights into the structure of the system, e.g. which variables are well connected and can be influenced in many ways, or which variables only have a few outbound connections with an immense impact on others. The workshop results offer an additional multitude of information about the components of the system and the impact of climate change on critical infrastructures and possible following cascading effects.

The results enable a categorization of the roles that the variables play in the system. In addition, questions about effective levers to initiate change as well as about variables with a stabilising influence can be investigated. Furthermore, variables can be identified that are critical to the system because of their strong interconnectedness, but that can at the same time be a threat due to potential side effects as a result of the high number of links in the system.

Quite striking was the fact that laws, regulations, and especially the Renewable Energy Sources Act (EEG) was discussed a lot, while the variables were only chosen once each (1x "regulation", 1x "EEG"). Also, a few variables were understood differently. Types of mobility, for instance, were not just understood as the variety of different means of transportation, but also in a much more absolute sense: "is transport/mobility in a crisis situation even still necessary? Who needs to remain mobile, who can stay put at least for a little while?". The variables chosen by the participants to be the most relevant for their work are shown in table 1.

- Share of electric vehicles (2x) - Specialists - European Network of Transmission System Operators for Electricity (ENTSO-E) - Regulation (e.g. EEG) (2x) - Flood risk	- Road/railway capacity - Road capacity (2x) - Communication - Types of mobility - Grid expansion - Network load	- Grid stability (4x) - Precipitation (2x) - Provision of public services - Volatility of renewable energy (2x) - Wind speed (2x) - Maintenance (2x)

Table 1: Most relevant variables

The results of the impact matrices for the three groups are highlighted in tables 2 to 4 below, whereby each group was named after a colour. In each table the digit "0" represents no impact, digit "1" a weak impact, digit "2" a proportional impact and digit "3" a strong impact.

Impact by ↓ on →	Share of electric vehicles	Network load	Grid expansion	Flood risk	Grid stability	Road capacity	Maintenance	Precipitation
Share of electric vehicles		2	2	0	2	0-1	0-1	0
Network load	-2		0-1	0	-3	0	0	0
Grid expansion	3	-2		0	3	0-1	0	0
Flood risk	0	0	0		0*	0-1	0	0
Grid stability	0	0	0	0		0	0	0
Road capacity	0	0	0	0	0		0	0
Maintenance	0	0	0	0	0	1		0
Precipitation	0	0	0	0-1	0	-2	1	

Table 2: Impact matrix of the "yellow" group

Impact by ↓ on →	Road/railway capacity	Wind speed	Grid stability	Provision of public services	Precipitation	Maintenance	Share of electric vehicles	Volatility of renewable energy	European transmission grid
Road/railway capacity		0	0	2	0	2	0	0	0
Wind speed	3		2	2	0	2	0	3	2
Grid stability	3	0		3	0	2	2	1	2
Public services	2	0	2		2	2	2	0	1
Precipitation	2	0	1	0		2	0	0	0
Maintenance	3	0	3	2	0		2	1	2
Share of electric vehicles	2	0	2	1	0	2		0	1
Volatility of ren. energy	0	0	3	3	0	2	0		3
European transmission	0	0	3	3	0	2	0	2	

Table 3: Impact matrix of the "blue" group

Impact by ↓ on →	Grid stability	Communi-cation	Wind speed	Regulation (e.g. EEG)	Volatility of renewable energy	Specialists	Types of mobility
Grid stability*		3	0	1	0	3/1	3
Communication**	3		0	0	0	3/2	3/2
Wind speed	2	1		1	3[1]	0	2
Regulation (e.g. EEG)	3	2	0		0	2	2
Volatility of renewable energy	3	1	2	2		1	2
Specialists***	3	2	0	2	0		2
Types of mobility****	2	2	0	1	0	3/1	

Table 4: Impact matrix of the "green" group

The fields with two numbers (distinguished with /) first show the intensity of impact during a crisis situation and secondly in a normal situation. *electricity/heat/transport; **using technological devices; ***not just general availability, but also availability at the right time at the right place; ****in a crisis situation, without electricity grid. 1 no sun, no wind ("Dunkelflaute").

Grid stability is the only variable mentioned in every group. But there are some differences in the results of each group as well. Most differences are linked to the variables grid stability and maintenance. Especially the "blue" and the "yellow" group disagree strongly about their impacts. Whereas the "blue" group was made up by experts of municipal companies, the majority of the participants of the "yellow" group were from the private sector. The "green" group consisted mostly of experts from the areas of administration and associations. For the "blue" group, maintenance and grid stability are crucial elements of a functioning critical infrastructure and therefore impacts many other variables strongly. The "yellow" group represents the users of a solid grid stability and well maintained critical infrastructure. They evaluate the impact on other variables of the system as less strong.

Impact by ↓ on →	Grid stability	Share of electric vehicles	European transmission grid	Specialists	Regulation (e.g. EEG)	Flood risk	Maintenance	Railway capacity	Road capacity	Communication	Types of mobility	Grid expansion	Network load	Precipitation	Public services	Volatility of ren. Energy	Wind speed	Active sum
Grid stability		0/2	2	2	1	0	0/2	3	0/3	3	3	0	0	0	3	0/1	0	**7-11**
Share of electric vehicles	2		1	-	-	0	1/2	2	1/2	-	-	2	2	0	1	-/0	-/0	**8**
European transmission grid	3	0		-	-	-	2	0	0	-	-	-	-	0	3	2	0	**4**
Specialists	3	-	-		2	-	-	-	-	2	2	-	-	-	-	0	0	**4**
Regulation (e.g. EEG)	3	-	-	2		-	-	-	-	2	2	-	-	-	-	0	0	**4**
Flood risk	0	0	-	-	-		0	-	1	-	-	0	0	0	-	-	-	**1**
Maintenance	0/3	0/2	2	-	-	0		3	1/3	-	-	0	0	0	2	-/1	-/0	**4-7**
Railway capacity	0	0	0	-	-	-	2			-	-	-	-	0	2	0	0	**2**
Road capacity	0	0	0	-	-	0	0/2			-	-	0	0	0	2	-/0	-/0	**1-2**
Communication	3	-	-	2	0	-	-	-	-		2	-	-	-	-	0	0	**3**
Types of mobility	2	-	-	2	1	-	-	-	-	2		-	-	-	-	0	0	**4**
Grid expansion	3	3	-	-	-	0	0	-	1	-	-		2	0	-	-	-	**4**
Network load	3	2	-	-	-	0	0	-	0	-	-	1		0	-	-	-	**3**
Precipitation	0/1	0	0	-	-	1	1/2	2	2	-	-	0	0		0	-/0	-/0	**4-5**
Public services	2	2	1	-	-	-	2	2	2	-	-	-	-	2		0	0	**7**
Volatility of ren. energy	3	-/0	3	1	2	-	2	0	-/0	1	2	-	-	-/0	3		-/0	**8**
Wind speed	2	-/0	2	0	1	-	-/2	3	-/3	1	2	-	-	-/0	2	3		**8-10**
Passiv sum	**11-13**	**3-5**	**6**	**5**	**6**	**1**	**6-9**	**6**	**6-8**	**6**	**6**	**2**	**2**	**1**	**8**	**2-4**	**0**	

Mentioned one-time
Mentioned two-times
Mentioned three-times

Table 5: Summarizing impact matrix of all groups

 ISBN 978-3-9504945-1-8. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER

The role of each of these variables – i) active, ii) reactive, iii) critical, iv) buffering, v) neutral – has been analysed as follows. According to Vester's original approach (Vester 1991; 2003), all participants should have discussed the relevance of all variables together in the workshop, to allow for a summarized evaluation and classification of their relevance in the overall system on the basis of the specific active and passive sums. Against the background of the first-time use of the method in this case study context, however, it was deviated from this in order to be able to implement and test the basic approach as simply and as low-threshold as possible with stakeholders. Depending on the experience with this initial application, it was originally planned to conduct a follow-up workshop in which the approach would be refined with additional stakeholders and applied in accordance with Vesters original approach. However, due to the Corona pandemic and the associated restrictions, this close exchange in the form of further workshops could not be carried out as planned. In order to nevertheless be able to derive initial results and insights into the overall relevance of the variables in the system, the results and assessments of the three subgroups were summarized in a comprehensive impact matrix. On the basis of this overall impact matrix, the specific active and passive sums have been calculated for the individual variables. This impact matrix and the corresponding results are shown in table 5.

Based on this, an allocation of the variables has been carried out in accordance with the five possible roles of the variables in the overall system, as outlined above (Vester 1991). Figure 2 shows this allocation. The difference of opinion concerning the variables maintenance and grid stability between publicly owned companies and private companies are visible again. Also, the two key climate parameters chosen by the workshop participants, wind speed and precipitation, have different roles in the system.

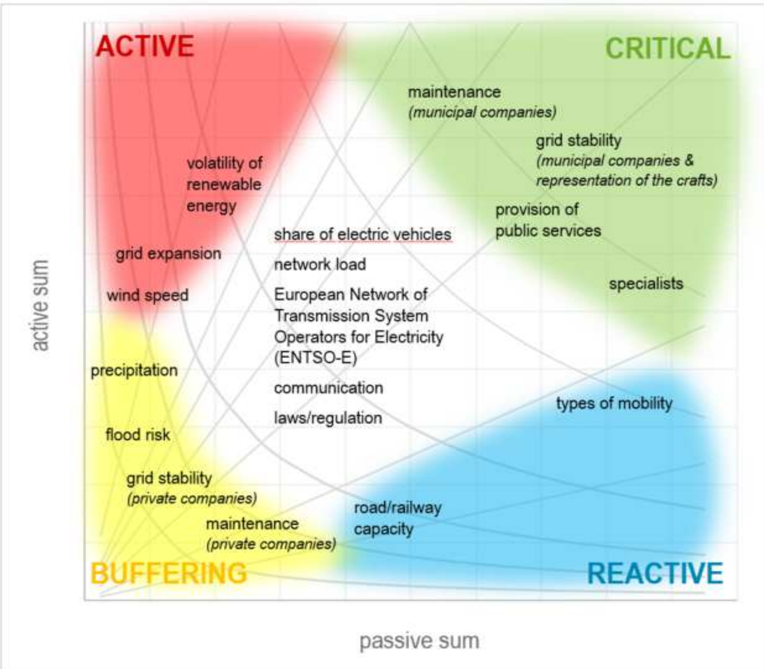

Fig. 2 – Assigned roles for each variable within the case study

Bases on these first results and experiences further need for research can be highlighted. So, for example, the relationships and interconnections between the variables should be investigated in more detail. Since the necessary data for this, might not be easily available, a first step could be to gather the experts' opinion and use a more qualitative approach, e.g. a Likert scale (Likert 1932) as a technique for the measurement of personal attitudes as well as a further development and testing of the paper computer concept by Vester (2003).

7 CONCLUSION

Enabling urban areas to adequately adapt to climate change with a focus on building and maintaining a resilient infrastructure and making cities and settlements safe, resilient and sustainable also requires fundamental transformations of central supply infrastructures as well as an improved understanding and comprehensive consideration of the interactions of these critical infrastructures under changing climatic conditions. To systematically capture the complex interlinkages of different infrastructure sectors under current and future climatic conditions and to account for potential cascading effects, an impact matrix approach has been applied and presented in this paper.

The results show, that both the interviews as well as the workshop provided valuable insights regarding the specific relevance of cascading effects for the sectors energy, water and transport. However, the applied method also has its limitations, as – for example – at this early stage it was only based on the perspectives of a small group of stakeholders, so that results are specific to their circumstances. Yet, it is expected that the outcome will be at least in parts transferrable to other regions or other infrastructure operators. Secondly, in order to investigate cascading effects, the links between the variables need to be identified and verified. Furthermore, knowledge about the impact level of a certain degree of change in one variable on another and about the time sequence revolving around this change is necessary to interpret and evaluate different scenarios and adaptation measures. This is an essential challenge because of the lack of data for most of the interdependencies in the system.

Furthermore, instead of focusing on the quantification of the non-representative results of the qualitative feedback loops between energy, water and transport in this case-study, it is recommended to also carry out further interactions with stakeholders and to develop the methodological approach. As mentioned, a follow up activity and integration of stakeholders could be a sensible measure to defining the feedback loops more concretely, based on the consensus of all participants, instead of small and rather homogenious groups. This would also be a way to figure out, how a diffent mix of stakeholders could have impacts on the outcome. Also, the development of possible scenarios can be discussed in collaboration with the stakeholders in order to expand and complement those scenarios typical to research with the perspective from practice.

However, even if some limitations remain, the process of interacting with experts was received positively as the stakeholders have been integrated in the process from the beginning. Also, for most of them, it was more or less the first real in-depth approach to deal with the topics adaptation to climate change and climate change related cascading-effects in this context. Therefore, this approach should be seen as a promising methodological starting point and role model for a further integration of stakeholders addressing the growing need to understand and manage systemic risks better regarding critical infrastructures and cascading effects in order to increase resilience to climate change impacts in urban areas.

Thereby key aspects of the "Agenda 2030" (United Nations 2015) – mainly the need to build and maintain a resilient infrastructure (goal 9) and to make cities and settlements safe, resilient and sustainable (goal 11) – are addressed. Furthermore, this overall approach is already in line with the recent 2020 "New Leipzig Charter" (European Commission 2020b). Besides highlighting the need to activate the transformative power of cities, it clearly points out participation and co-creation as key principles of good urban governance in a sense that it requires the involvement of the general public as well as local experts – social, economic and other stakeholders – in order to consider their concerns and knowledge. Furthermore, the "New Leipzig Charter" clearly addresses the cities' need for steerability and shaping of infrastructure, public services and public welfare. This includes services for health, social care, culture, water and energy supply, waste management, public transport, digital networks, information systems and public spaces as well as green and blue infrastructures (European Commission 2020b).

8 REFERENCES

Andersen DF, Richardson GP (1997): Scripts for group model-building. System Dynamics Review 13 (2): 107-129.

Andersen DF, Richardson GP, Vennix JAM (1997): Group Model-Building: adding more science to the craft. System Dynamics Review 13(2): 187-201.

Bar-Yam Y (2002): General Features of Complex Systems. Encyclopedia of Life Support Systems (EOLSS) Oxford.

BBK and BSI (2020): Schutz Kritischer Infrastrukturen. Gefahren, Strategien und rechtliche Grundlagen, Akteure, Aktivitäten und Projekte zum Schutz Kritischer Infrastrukturen in Deutschland. (BSI). Glossar: Kritische Infrastruktur.

Bérard C (2010): Group model building using system dynamics: an analysis of methodological frameworks. EJBRM 8 (1): 35-46.

BfG (2019): Das Niedrigwasser 2018. Bundesanstalt für Gewässerkunde. Koblenz.

BMI (2009): Nationale Strategie zum Schutz Kritischer Infrastrukturen (KRITIS-Strategie). Bundesministerium des Innern. Berlin.

Ciscar J-C, Dowling P (2014): Integrated assessment of climate impacts and adaptation in the energy sector. Energy Economics 46: 531-538.

EEA (2020): Urban adaptation in Europe: how cities and towns respond to climate change. EEA Report No 12/2020. Kopenhagen.

EEA (2019): Adaptation challenges and opportunities for the European energy system. Building a climate□resilient low□carbon energy system. EEA Report No 1/2019. Kopenhagen.

European Commission (2020a): Proposed Mission: A Climate Resilient Europe: Prepare Europe for climate disruptions and accelerate the transformation to a climate resilient and just Europe by 2030. Report of the Mission Board for Adaptation to Climate Change, including Societal Transformation.

European Commission (2020b): New Leipzig Charter- The transformative power of cities for the common good.

Eusgeld I, Nan C, Dietz S (2011): System-of-systems approach for interdependent critical infrastructures. Reliability Engineering System Safety 96 (6): 679-686.

Forrester JW (2007a): System dynamics—a personal view of the first fifty years. System Dynamics Review Vol. 23, No. 2/3, (Summer/Fall 2007): 345–358.

Forrester JW (2007b): System dynamics—the next fifty years. System Dynamics Review Vol. 23, No. 2/3, (Summer/Fall 2007): 359–370.

Forzieri G et al. (2018): Escalating impacts of climate extremes on critical infrastructures in Europe. Global Environmental Change 48: 97-107.

Frantzeskaki N, Loorbach D (2010): Towards governing infrasystem transitions: Reinforcing lock-in or facilitating change? Technological Forecasting and Social Change 77 (8): 1292-1301. doi:10.1016/j.techfore.2010.05.004.

Funabashi Y, Kitazawa K (2012): Fukushima in review: A complex disaster, a disastrous response. Bulletin of the Atomic Scientists 68 (2): 9-21.

Groth M, Bender S, Cortekar J, Remke T, Stankoweit M (2018): Auswirkungen des Klimawandels auf den Energiesektor in Deutschland. Zeitschrift für Umweltpolitik und Umweltrecht 3: 324-355.

Hänsel S, Herrmann C, Jochumsen K, Klose M, Nilson E, Norpoth M, Patzwahl R, Seiffert R (2019): Verkehr und Infrastruktur an Klimawandel und extreme Wetterereignisse anpassen. Bundesministerium für Verkehr und digitale Infrastruktur (BMVI). Berlin.

Hassel, H., Johansson, J., Cedergren, A., Svegrup, L., Arvidsson, B. (2014): Method to study cascading effects. Deliverable 2.1, Modelling of dependencies and cascading effects for emergency management in crisis situations (CascEff Project).

IPCC (2018): Global warming of 1.5°C. Special Report. IPCC with World Meteorological Organisation (WMO and United Nations Environmental Program (UNEP), 616 S. Geneva (2018).

Johansson J, Svegrup L, Arvidsson B, Jangefelt J, Hassel H, Cedergren A (2015): Review of previous incidents with cascading effects.

Karagiannis GM, Chondrogiannis S, Krausmann E, Turksezer ZI (2017): Power grid recovery after natural hazard impact, JRC Science for Policy Report No EUR 28844 EN. Publications Office of the European Union. Luxembourg. doi:10.2760/87402.

Laugé A, Hernantes J, Sarriegi JM (2015): Critical infrastructure dependencies: A holistic, dynamic and quantitative approach. International Journal of Critical Infrastructure Protection 8: 16-23. doi:10.1016/j.ijcip.2014.12.004.

Leventon J, Fleskens L, Claringbould H, Schwilch G, Hessel R (2016): An applied methodology for stakeholder identification in transdisciplinary research. Sustainability Science 11: 763-775. doi:10.1007/s11625-016-0385-1.

Likert R. (1932): A technique for the measurement of attitudes. Archives of Psychology, 22 140, 55.

Lückerath D, Olfert A, Milde K, Ullrich O, Rome E, Hutter G (2020): Assessment of and tools for improving climate resilience of infrastructures: Towards an ERNCIP Thematic Group. Input Paper.

Lugo AE (2019): Social-Ecological-Technological Effects of Hurricane María on Puerto Rico. Planning for Resilience under Extreme Events. Springer International Publishing. Cham.

Luiijf HAM, Nieuwenhuijs AH, Klaver M, van Eeten MJG, Cruz E (2010): Empirical Findings on European Critical Infrastructure Dependencies. International Journal of System of Systems Engineering 2 (1): 3-18. doi:10.1504/IJSSE.2010.035378.

Meadows, D (2008): Thinking in systems: a primer / Donella H. Meadows; edited by Diana Wright. p. cm. White River Junction, VT, USA: Chelsea Green Publishing.

Meadows DH, Meadows DL, Randers J, Behrens III WW (1972): The Limits to Growth; A Report for the Club of Rome's Project on the Predicament of Mankind. New York: Universe Books. ISBN 0876631650.

Meusel D, Kirch W (2005): Lessons to be Learned from the 2002 Floods in Dresden, Germany. In: Kirch W, Bertollini R, Menne B (Hrsg) Extreme Weather Events and Public Health Responses. Springer. Berlin, Heidelberg, S 175-183.

Mikellidou CV, Shakou LM, Boustras G, Dimopoulos C (2018): Energy critical infrastructures at risk from climate change: A state of the art review. Safety Science 110: 110-120.

Moss T (2014): Socio-technical Change and the Politics of Urban Infrastructure: Managing Energy in Berlin between Dictatorship and Democracy. Urban Studies 51 (7): 1432-1448.

Nilson E, Astor B, Bergmann L, Fischer H, Fleischer C, Haunert G, Helms M, Hillebrand G, Höpp S, Kikillus A, Labadz M, Mannfeld M, Razafimaharo C, Patzwahl R, Rasquin C, Rauthe M, Riedel A, Schröder M, Schulz D, Seiffert R, Stachel H, Wachler B, Winkel N (2019): Beiträge zu einer verkehrsträgerübergreifenden Klimawirkungsanalyse: Wasserstraßenspezifische Wirkungszusammenhänge. Bundesministerium für Verkehr und digitale Infrastruktur (BMVI). Berlin.

Reed MS, Graves A, Dandy N, Posthumus H, Hubacek K, Morris J, Prell C, Quinn CH, Stringer LC (2009): Who's in and why? A typology of stakeholder analysis methods for natural resource management. Journal of Environmental Management 90 (5): 1933-1949.

Rinaldi SM, Peerenboom JP, Kelly T K (2002): 'Identifying, understanding, and analyzing critical infrastructure interdependencies', IEEE Control Systems, 21(6), pp. 11–25.

Siokou C, Morgan R, Shiell A (2014): Group model building: a participatory approach to understanding and acting on systems. Public Health Research and Practice 25 (1): e2511404.

Sterman, JD (2001): System Dynamics Modeling: Tools for Learning in a Complex World. California Management Review, 43(4), 8–25.

United Nations (2015): Transforming our world: the 2030 Agenda for Sustainable Development.

Vennix J (1996): Group model building: facilitating team learning in system dynamics. Hoboken, NJ: John Wiley and Sons Ltd.

Vester F (2003): Die Kunst vernetzt zu denken. Ideen und Werkzeuge für einen neuen Umgang mit Komplexität. Der neue Bericht an den Club of Rome. Munich: dtv. 3rd edition.

Vester F (1991): Material zur Systemuntersuchung: Ausfahrt Zukunft Supplement, München, p. 96.