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Linking critical infrastructure resilience to social vulnerability through minimum supply concepts: review of gaps and development of an integrative framework

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Abstract.

Increased attention has lately been given to, first, social vulnerability reduction and, second, critical infrastructure management in the context of natural hazards and disasters. However, strikingly little efforts have been made in linking the two in a coherent manner conceptually and practically. Addressing this gap is the objective of this paper. In its first part, it provides a structured review on achievements and remaining gaps in the management of critical infrastructure and the understanding of social vulnerability towards failures during and after disasters. Special attention is given to the current state of minimum supply concepts. In its second part, the paper then responds to the identified gaps by developing a novel conceptual framework on the linkages of critical infrastructure management, social vulnerability and minimum supply. The framework is meant to guide future research as well as policy making and practical action. It facilitates and guides the conceptualization of (i) causal relationships between these three components, (ii) the assessment of system states in each component and (iii) the normative and political choices that need to be made explicit and tackled for turning the concept into policy and action. The paper closes by sketching out recommendations for a future research and practice agenda to close the detected gaps.

1. Introduction: Why the integration of critical infrastructure, social vulnerability and minimum supply matters

Critical infrastructure plays a key role in shaping a society's vulnerability towards natural hazards and the resulting risk of disasters (cf. Grubesic & Matisziw 2013, Sage et al. 2015, Pescaroli & Alexander 2016). Infrastructure for electricity, water, transport, health and law enforcement, for example, plays a critical role for the day-to-day functioning of a society. Yet the importance of such infrastructure becomes particularly evident in situations of disasters and crises, when critical infrastructure is prone to fail, thereby causing wider impacts on the society. The vulnerability and/or resilience of critical infrastructure itself is therefore increasingly moving into the focus scientists, risk practitioners and political decision-makers (cf. Critical 5 2014, 2015, Herzog & Roth 2014, McGee et al. 2015). This attention is further driven by the growing role of critical infrastructure resulting from the rising societal dependence on technology, the ever-growing connectedness of infrastructure systems in the age of information technology and the growing global connectedness of people, production, trade and communication (Collins et al. 2011, Miles 2015).

However, while increasing attention has lately been given to assessing the exposure and sensitivity of critical infrastructures and the crises contingencies in their management (e.g. through so-called stress tests of nuclear power plants in the European Union following the Fukushima disaster), it remains highly questionable whether such a focus sufficiently captures the wider linkages between critical infrastructure failure and social vulnerability in a society at large. Anecdotal evidence and structured expert dialogues[1] suggest that risk in relation to critical infrastructure failure is currently captured in rather narrow and technocratic ways, focusing largely on technical parameters of individual infrastructure branches (e.g. water supply or power generation) whilst failing to sufficiently capture the wider effects of critical infrastructure failure on societal risk and risk cascades (e.g. disruption in water supply due to electricity black-outs or a standstill of public transportation due to disruptions in ICT technology). Most importantly, however, it seems that the technical discourse on critical infrastructure failure does not adequately link into the domain of social vulnerabilities. It is not well understood which differential impacts critical infrastructure failure will have on different parts of the society (e.g. different age groups, neighborhoods, people with special need for care) and how these differential impact patterns relate to different hazard and crises scenarios (e.g. a power black-out during a summer heatwave, affecting the potential for air conditioning and water supply, versus a flood-induced black-out during autumn or winter, taking effect on issues such as electric heating).

Social vulnerability studies provide powerful analytical lenses to approach such questions. Vulnerability thinking is, at its course, tailored to bring together (hypothetical) hazard scenarios with the societal predispositions for suffering harm when affected by such hazards (Blaikie et al. 1994). One of the core interests in vulnerability studies has therefore always been to ask whether and how hazards and crises (such as a compound flood-cum-blackout hazard) take differentiated effects on different groups within society.

For the management of critical infrastructure failure, the vulnerability perspective also begs important scientific, normative and political questions with respect to the linkages between critical infrastructure failure, social vulnerability and minimum supply: Which levels of minimum supply (e.g. of electricity and water) are needed to avoid disastrous effects of natural-hazard-induced infrastructure failure? How are these minimum supply requirements perceived to differ between social groups (e.g. single elderly vs. family households or rich vs. poor neighborhoods) as well as between different other infrastructure elements (e.g. hospitals vs. water treatment plants vs. shopping malls)? Who ought to be responsible for securing a level of minimum supply (e.g. state authorities vs. private households)? Such debates are far from being at the core of ongoing discourses, posing serious questions about preparedness. One example is the 2016 German Civil Defense Plan requiring Germans to stockpile

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[1] For example within the Expert Roundtable Discussion on "Integrated Research for Enhancing the Resilience of Critical Infrastructures through Strategic Assessments and Innovative Planning Approaches", sponsored by the German Research Foundation and hosted by the University of Stuttgart on 26-27 October 2016 (http://www.uni-stuttgart.de/ireus/forschung/Initiativen/index.html), or within the expert meetings during the design phase of the KIRMIN project (http://ehs.unu.edu/research/critical-infrastructures-resilience-as-a-minimum-supply-concept-kirmin.html#outline), now sponsored by the German Federal Ministry for Science and Education.

private supplies. Instead of being taken serious the plan rather caused ridicules, indicating an overreliance in continuous infrastructure provision, making the German case particularly interesting to look at.

Against this background, the paper sets out examine the problematic nexus of critical infrastructure failure, social vulnerability and minimum supply. It has two main objectives: First it aims at exploring the current state-of-art regarding the scientific understanding and practical / political approaches on this nexus. This analysis is driven by a comprehensive review of academic literature as well as policy and planning documents in the most relevant communities of practice. Second, and building on the gaps identified in the first part, the paper develops and novel conceptual framework that is argued to help structure emerging questions and future agendas of scientists, risk practitioners and political decision-makers concerned with limiting the social effects of critical infrastructure failure.

The next section of the paper will present the methods and result of the global literature review. The third section will develop and present the proposed conceptual framing of the nexus between critical infrastructure (CI) failure, social vulnerability and minimum supply. The fourth section discusses resulting gaps in research and practice. The last section draws key conclusions.

2. Methodology: Data sources and methods of analysis

In order to get a more detailed understanding of how science, practice and policy has been dealing with the intersection of critical infrastructure management, social vulnerability reduction and minimum supply, we conducted a comprehensive literature and document review. It covered three main fields of information: First, we reviewed scientific literature. A structured document search was conducted in the Scopus database in July 2017, which captures a wide range of academic literature, including most of the peer-reviewed journal articles, book chapters and proceedings of internationally important conferences. We applied different key word searches in order to identify relevant contributions. Figure1 provides an overview over the search combinations and respective results. In a second step, we did a content analysis of the abstracts of the resulting documents in order to group the contributions into three groups: explicitly relevant (i.e. contributions that explicitly talk the linkages between CI failure and/or social vulnerability and/or minimum supply), implicitly relevant (i.e. contributions which to not primarily target these linkages, e.g. in their titles and objectives, but nevertheless address them indirectly or as a side product or in the description of a certain disaster event) and not relevant (i.e. contributions shortlisted by the keyword search but not making relevant statements to the nexus of interest here). In cases where the abstracts did not allow for a clear allocation, we analyzed the entire article. Overall as little as fifteen papers were found directly linked to the core topic of this paper, while another 79 provided implicit information.

The second body of data captured in the analysis is composed of legal, policy and practice documents, published by national or international authorities and organizations. Identified by strategic google-searches and snowball-sampling from other sources, the final set of data analyzed in this group contained 73 documents, with over 4,500 pages in total. Different from the first body of scientific literature, focus of these documents is a more applied one, mostly aiming at regulating or defining different infrastructure standards or at disseminating information on preparedness. In terms of the legislative documents, a regional focus was put on Germany and the EU since policies could not be assessed for each country on a global scale and this research was conducted as part of the research project "KIRMin - Critical Infrastructures Resilience as a minimum Supply Concept" focusing on a German case study. The policy and practice documents covered publications by international, European and German organizations working in the field of disaster risk reduction and civil protection (e.g. the United Nations Office for Disaster Risk Reduction) as well as research councils, consultancies and other bodies.

All documents in both streams were then analyzed through an in-depth content analysis. For that purpose, a coding system was developed and manually applied to the documents (roughly 5,500 pages in total), using MaxQDA software. The analysis was therein guided by the following questions:

- How are critical infrastructures (CI), minimum supply and social vulnerability to CI failures dealt with in terms of:
  - definitions;
  - legal responsibility and other relevant actors;
  - thematic foci, context of application and cases;
  - detected gaps within and between CI, minimum supply and social vulnerability.

3. Literature Review: Current treatment of critical infrastructure

A number of clear patterns and trends can be discerned from the analysis. First, the overall number of scientific publications dealing with critical infrastructure in the context of disaster risk has been rapidly rising since the early 2000s (Figure 2), indicating the growing significance of the topic. The increase can be ascribed to a mounting recognition of critical infrastructure protection on national levels since the mid-1990s. During this time, for instance the US President's Commission on Critical Infrastructure Protection (PCCIP) was created (Dahlberg et al. 2015). Over the next years several other countries followed with own programmes on infrastructure protection (Lindovsky 2014). The review suggests that a major focus CI protection was on terrorist attacks, natural hazards and industrial disasters (see also Rey 2013).

However, in thematic terms also a number of key differences can be identified. In absolute numbers papers dealing with disaster resilience and social vulnerability have increased most over time although a large number is not exclusively related to CI but rather names infrastructures as one source of vulnerability in the context of disasters. In parallel also a notable increase of publications on CI and preparedness as well as on CI and disaster resilience can be observed. At the same time only very few papers are available which focus on minimum supply or minimum requirements for critical infrastructure and the related social vulnerability.

The vast majority of scientific papers analyzed are written from a rather technological point of view. They hence concentrate heavily on technological challenges with CI systems and their management. If challenges beyond such technological perspectives are considered, they mostly revolve around the management of CI, especially in terms of transboundary

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management as well as public-private constellations (cf. NATO 2007, Smedts 2010). End users – whether businesses or households – tend, if mentioned at all, to be treated as rather passive recipients who face difficulties in case of CI failures. Businesses are mostly mentioned in the context of economic damages in case of CI disruption, while individuals or households remain mostly generalized without referring to specific societal groups with distinct demands.

The case studies given in the body of literature can be divided into two main groups. While cyber-attacks and ICT failures are mentioned in a number of papers there are hardly any concrete cases assessed extensively. Concrete case studies are rather limited to disasters induced by natural hazards, mostly flooding as well as storms and snow storms. Also a regional focus on cases from developed countries and particularly the US could be detected. Especially the impacts of hurricanes Katrina (cf. Oh et al. 2010, 2013, Grigg 2012, Grubesic & Matisziw 2013, Urlainins et al. 2014, Kelman et al 2015, Cutter 2016), and Sandy (cf. Kelman et al 2015, Pescaroli & Alexander 2016) have been assessed in a number of scientific publications. Economic impacts make for the predominant emphasis in such assessments (e.g. Oh et al. 2010, Chopra & Khanna 2015, Pant et al. 2016, Critical 5 2015) as e.g. in the case of the Fukushima event in 2011 (UNISDR 2014, Urlainis et al. 2014, Pescaroli & Kelman 2017). Another emphasis is put on the need for improved preparedness in these countries (e.g. Kaneberg et al. 2016). Papers on disasters in developing countries (e.g. the earthquake in Haiti) rather focus on humanitarian impacts from CI failure (e.g. Oh et al. 2013, Urlainis et al. 2014, Pescaroli & Kelman 2017).

Apart from very few exceptions (policy documents: D-A-CH 2013, BMI 2016, as well as few research papers: Pye et al. 2011, Oh et al. 2013, Miles 2015, Pescaroli & Alexander 2016), there is a distinct lack of documents that discuss critical infrastructure resilience, minimum supply and social vulnerability in an integrated manner – or even name the three elements in the same document. They all share a non-technocratic perspective that addresses societal demands. The following sections will provide a more detailed analysis on current debates regarding these three topics across all types of documents analyzed (Figure 3).

3.1 Critical infrastructure and critical infrastructure resilience

Definitions of critical infrastructure originate almost exclusively from policy and legal documents. Definitions and sectors of critical infrastructures vary between different countries, although most would comprise energy, water, food, transport, telecommunications, health, as well as banking and finance (Ridley 2011). In the German context CI is defined as "organisational and physical structures and facilities of such vital importance to a nation's society and economy that their failure or degradation would result in sustained supply shortages, significant disruption of public safety and security, or other dramatic consequences" (BMI 2009). A review of the academic papers suggests that defining CI is not a research topic in itself, as definitions in research documents are either taken from policy, e.g. national definitions, or are adapted from these sources.

The responsibilities for CI management in disaster situations are particularly addressed in policy documents. Across most contexts and sectors, duties and responsibilities are shared between governmental authorities and private infrastructure providers, the latter of whom usually take care of the supply under normal conditions. This is also the case in Germany, where despite existing policies such a shared responsibility has the potential to result in murky responsibilities with unclear risk burdens and liability in crises situations (Van Aaken & Wildhaber 2015) : Estimates suggest that around 80% of Germany's critical infrastructures are managed by private operators or are state-owned enterprises (BBK 2010b), e.g. there are overall around 370,000 operators in the food production sector (BSI 2015a). While these suppliers are responsible for the continuous supply, governmental authorities take responsibility for delivery by providing the framework conditions to protect CI (BMI 2005, BBK 2012, UP-KRITIS 2014a, 2014b, 2016). In the German case responsibilities for protecting CI are mainly with the Federal Ministry of the Interior and its subsidiary organizations, particularly the Federal Office for Civil Protection and Disaster Response and the Federal Office for Information Security BSI (BSI 2015b). The primary responsibilities for civil protection however are on the Federal State levels (BMI 2005). Each federal state has its own disaster management law while there are national laws for different aspects of CI such as water (BMJV 1970) or food supply (BMJV 2017) and IT (BSI 2015, Kaschner and Jordan 2015, Dietzsch et al. 2016). In case of a CI failure triggered e.g. by natural hazards like floods responsibilities will be located with governmental authorities at the affected level, depending on the scale of the event either at district, federal state or national one (BBK 2015a). Overall CI protection is focusing almost exclusively on assigning responsibilities and defining technical standards, not only in Germany but also in other European countries like Austria (Bundeskanzleramt Österreich 2015) or Switzerland (Lauta 2015, VBS & BABS 2016).

Policy challenges, e.g. coordination among EU countries, are addressed both in policy documents (CEPS 2010, EC 2016a, Commission of the European Communities 2006, EC 2008, 2012, 2013) and research papers (Kaneberg et al. 2016, Rehak et al. 2016). In addition, several research papers also raise doubts about lacking policies and unclear responsibilities (Van Aaken and Wildhaber 2015, Kitagawa et al. 2016),

Policy literature has a strong and growing focus on resilience-based approaches for CI protection (CEPS 2010, D-A-CH 2013, Brasset and Vaughan-Williams 2015, McGee et al. 2015). A growing number of countries has either adopted a resilience framing to CI over the past years, e.g. Australia (JRS-IPSC 2012), Canada and New Zealand (New Zealand Government 2011, Critical five 2014) or shows tendencies to focus more on resilience issues, such as the US (Dahlberg et al. 2015), the EU and various European countries (Brasset and Vaughan-Williams 2015, UP KRITIS 2014b). Here CI resilience is almost exclusively seen in a rather technological perspective with a focus on continuous provision or timely recovery of CI services even in times of hazards, crises and disasters (Collins et al 2011, D-A-C-H 2013, Ortenzy 2013, Münzberg et al. 2015).

Also the academic literature has a strong focus on technological perspective towards CI resilience (Pye et al. 2011, Cimellaro 2014, Liu et al. 2014, Pregnolato et al. 2016) although some papers raise questions on shortcomings of a limited technological perspective. Sage et al. (2015) call for a more socio-ecological understanding of infrastructure which is in line with Comes (2016) who claims that although communities are recognized as being at the heart of resilience, research still focuses on more on responders instead of considering individuals or local communities as actors. Empirical studies on CI resilience are still rare and "still focus on activities within the boundaries of the CI" (Labaka et al. 2014: 431) and much less on the "well-being of all citizens through the availability of essential goods and services" (Ridley 2011: 111), underlining the demand for more studies on community or societal group level.

3.2 Minimum supply

There is no universal definition of minimum supply with critical infrastructures, neither in research nor policy or legislation. If at all minimum supply levels are rather given for different infrastructures. Minimum supply with CI is tackled predominantly in policy (e.g. BMJV 1970, 2017, EC 2016b) or even humanitarian relief publications (e.g. IFRC 2011, IRP 2010, UNISDR 2014) and to a much lesser extent in the scientific community.

In the German context a huge number of documents from governmental authorities is available to inform citizens about private precautionary measures, including the stockpiling of minimum supplies as preparatory measure for potential blackouts. The 2016 civil defense strategy recommends German citizens to get equipped with food for ten days and two liter of potable water for a period of five days as well as to keep warm clothing and blankets in stock to cope with power outages (BMI 2016). On the supply side the German water security law (Wassersicherstellungsgesetz) calculates a vital supply of 15 liter of drinking water/day/capita for each citizen, but 75 liter/day/bedside for hospitals and healthcare facilities and 150 liter/day/bedside for surgery and infection facilities or respective departments for at least 14 days in case of crisis (BMJV 1970).

Further, both documents (BMI 2016, BBK 2016c) recommend private equipment of necessary medical equipment and to prepare for short-term power outages However, except for medicine there is no differentiation between societal groups. Other publications also recommend backup generators or other devices to compensate (longer) power outages (BBK 2010a, BBK 2015b). For some critical infrastructures there are no regulations to maintain minimum functions, e.g. for sewage where no backup generators are demanded in case of a power outage (BBK 2010a).

Besides policy it is the humanitarian literature that gives some guidance on minimum standards, although mostly limited to water, food and health. Among others the SPHERE handbook (IFRC 2011) provides guidance on minimum supply with water, food, and others in case of disaster, however it does not mention critical infrastructures as such, indicating a potential missing link between the views of infrastructure and humanitarian communities on minimum standards. Scientific literature in this field seems still scarce.

Responsible actors for minimum supply are basically the same as for the regular supply with critical infrastructures. In declared emergency situations the command is transferred to crisis units with governmental actors, who then would also be allowed to intervene in private suppliers' decisions. In addition actors from emergency response like civil defense authorities, fire brigades or actors from healthcare are involved in supplying population in need. Furthermore the population itself is held at least partly responsible for their own basic supply, as e.g. recommended in the civil defense strategy (BMI 2016). But a discussion of the role of actors and their responsibilities is almost entirely limited to policy documents.

A gap detected in both bodies of documents related to the question how minimum supply demands differ among societal groups. Policy sources were found to distinguish only between demands for healthcare (e.g. different supply levels for hospitals) but rather view 'the population' in a uniform way. Even scientific papers provided only few statements on minimum or failed supply of local communities or distinct vulnerable societal groups. In a study on healthcare infrastructure in Ghana, Kenya, Rwanda, Tanzania and Uganda Hsia et al. (2012) found that less than 65% of all hospitals have basic infrastructure components such as reliable sources of water and electricity. This is far the below the level of coverage recommended by the World Health Organization (WHO). Miles et al. (2011) report that in case of a blackout in San Diego, USA, patients are transported to those healthcare facilities that have backup generators. Münzberg et al. (2015) discuss the importance of knowing the critical point in time at which all backup capacity is depleted.

3.3 Social vulnerability

Both bodies of documents address vulnerabilities in relation to CI failure. However, the vast majority focusses on vulnerabilities of the critical infrastructures themselves and ways to reduce that vulnerability, without defining it further. Social vulnerabilities are mentioned – if at all – only briefly and vaguely. A significant gap was therefore detected, which applies to both fields (research and application).

Most of the policy documents e.g. in the German context, stress the vulnerability to CI failures of the population at large and stress private prevention measures (e.g. BBK 2015a, BBK 2016b, BBK 2015b). The review suggests that the only context in which differential vulnerability within the society is discussed explicitly is the health sector. In a crisis situation with limited availability of medical services, the classification and prioritization of groups of patients, based on survival rates and available resources, seems to be widely accepted across different contexts (Rosenbrock & Gerlinger 2004, Christian et al. 2014, BSI 2016). Differences between rural and urban communities are mentioned in case of emergency water supply, where scarcely populated rural areas pose bigger challenges for authorities to provide the statutorily determined minimum supply (BBK 2013, BBK 2016a).

A few research papers address the relationship between CI, (social) vulnerability and supply problems in past CI failures. However there was not a single paper for which this relationship provided the major or explicit emphasis. Rather, the few documents addressing the relationship did so on a side note, e.g. mentioning risks for dialysis patients in need of healthcare facilities with energy backup systems during 2011 Hurricane Sandy (Kelman et al. 2014, Pescaroli and Alexander 2016) and a power outage in San Diego in the same year (Miles et al. 2014). The San Diego event was particularly problematic for low-income households that could not afford backup power and faced problems with the unexpected need to facilitate the replacement of food stamp benefits (Miles et al. 2014). Reports on other events describe a general societal vulnerability to CI failures, e.g. in the case of the 1998 ice storm in Canada (CEPS 2010, Chang et al. 2007), or the severe snow storms in 2005 in Münsterland, Germany, where affected people were not able to purchase food in local stores due to power outages (BMI 2015, BSI 2015, Menski & Gardemann 2008). Hunter et al. (2016) studied 45 local health departments in 20 US states and found certain groups to be more vulnerable to power outages, in particular elderly, people living in high-rise buildings, and persons dependent on medical devices like home ventilators.

Research literature highlights three groups and their vulnerability to long-term critical infrastructures disruptions: the elderly (Urlainis et al. 2014), people in need of healthcare and low-income households. In addition the place of residence matters, i.e. in a case study in Virginia, USA, Liu et al. (2015) found urban settlers more vulnerable to impacts from flood and storm surge but rural dwellers more vulnerable considering related CI access (cf. Liu et al. 2015). Vulnerable groups also often live in places with above-average vulnerability at large (cf., Liévanos & Horne 2017). Other studies linked poverty to less preparedness to disasters, e.g. if healthcare is anyway weak (cf. study of Banks et al. (2016) in central Appalachia, USA), or if food security is not given (e.g. Cutter (2016) in the case of Hurricane Matthew's impacts on North and South Carolina, USA).

Social vulnerabilities interact with CI failures and are likely to amplify disaster impacts. As a consequence CI failures with relatively minor impacts in one locality may have major ones in another place (McGee et al 2014:13). These differences and the potential of individual or community preparedness for CI failures are however addressed by very few papers only. Grigg et al. (2012) claim a culture of citizen and community preparedness in the context of Hurricane Katrina (Grigg 2012, Moore et al. 2007). During a 2013 snowstorm in Jordan (Sawalha 2014) witnessed a lack of community cooperation which could have supported the restoration of basic community services.

In the end it is the individuals' preparedness to CI failures that is heavily contributing to societal resilience (Petit et al. 2011). CI (minimum) supply in case of a disaster in the end is a question of ethical choices -- who does receive how much and based on which reasons? Addressing these questions requires and understanding of CI systems that goes beyond the purely technical dimensions (Pye et al. 2011, Sage et al. 2015). However aspects of fairness of CI supply and related ethical debates are rather tackled in humanitarian literature (IFRC 2011, Moodley et al. 2013)) but much less in CI policy (EC 2016b) and research where it seems to be a blind spot. In the German context for instance growing demands of more people hospitalized or in need of home care would call for studies on the question in how far their emergency supply could be sustained (BBK 2012b).

As summarized in Figure 4, there are few gaps in defining CI and CI management and the related actors as well as their responsibilities. Particularly social vulnerabilities to CI failures are hardly dealt with in CI research and policy. Thus, a significant gap in research on the vulnerabilities of different social groups to CI outages as well as related policies was detected. In addition, potential mutual intensification or reduction of minimum supply and social vulnerabilities are greatly neglected.

4. Framing the relationships between critical infrastructure, social vulnerability and minimum supply

Building on the results of the review, Figure 5 provides a framework for capturing the relationship between critical infrastructure failure, minimum supply and social vulnerability. We argue that the impacts from critical infrastructure failure are modulated – i.e. amplified and/or mediated – by social vulnerability as well minimum supply. The latter two are in turn coupled in a functional and normative relationship. In line with the use in risk and disaster research, vulnerability is understood here as the predisposition of social actors to suffer harm when exposed to a hazard (Wisner et al. 2004). The immediate hazard can in this context be the failure of critical infrastructure supply such as water or electricity which, in turn, can be triggered by other hazards, for instance floods, tsunamis, storms or other non-environmental hazards such as terrorist attacks. The analysis of social vulnerability towards critical infrastructure failure has the potential to inform the planning and design of minimum supply schemes – and it should do so in our eyes. In return, a secured minimum supply can defuse social vulnerability and therefore buffer otherwise higher impacts. Given the modulating effects of minimum supply and social vulnerability, the resulting impacts from critical infrastructure failure can therefore be higher or lower. In any case, the impacts can be expected to be differentiated socially, spatially and functionally.

5. Discussion: A future agenda for science and practice

In combination of the gaps identified in the review (section 2) and the conceptual framing (section 3) we argue that a number of needs can be identified that can drive future science, practice and policy agendas:

In terms of scientific knowledge, considerable knowledge gaps remain with regards to the ways in which different parts of the society are vulnerable differently to the failure of critical infrastructure and the resulting lack of supply with goods and services, most importantly water and electricity. While vulnerability assessment in in the context of environmental hazards has made great methodological advancements over the last years (Birkmann 2014), this literature has almost exclusively referred to the direct and immediate influences of environmental hazards, e.g. how vulnerable households if affected immediately by flooding. In addition to this focus vulnerability assessment concepts and methods also need to be applied – and adjusted – to assess the secondary effects of natural hazard impacts emerging from CI failure. This is not an easy task, given that in many contexts social actors cannot draw on experiences with respective reference scenarios. Estimating one's own vulnerability, i.e. predisposition for suffering harm, in case of, for example, an extended blackout or water shortage might therefore prove difficult.

An additional challenge deserving attention is the potentially fine-gridded differentiation across social groups, space and time. While such differentiation is a common property of vulnerability in many contexts, it is particularly challenging for the context of minimum supply. This is because the infrastructure behind most services, e.g. electricity and water, is designed for larger system entities. For instance, the social vulnerability towards suffering impacts from a sustained blackout might differ within a single multi-apartment block, e.g. comparing an elderly and immobile person with a cardiovascular disease and dependence on electrical medical equipment to a group of young students sharing the apartment next door. Yet at the same time, the electricity grid cannot deliberate supply on such a high resolution as it functions in much larger entities, e.g. switching on or off entire neighborhoods of a city. Question of timing complicate the situation even further, as secondary concerns such as power for food production facilities can become primary concerns over time, in case of a prolonged CI failure.

Apart from these rather technical scientific problems, a set of very important questions emerges at the science-policy interface with respects to normative and procedural issues of distributional justice and responsibility. The review of practical management contingencies and legal as well as policy documents (section 2) suggests that practice and policy has been cautious in defining minimum supply levels for few critical infrastructure sectors – however they hardly differ for different social groups, regions, secondary infrastructure etc. While it seems to be easier to provide numbers for certain sectors, e.g. for water supply (see above), for other sectors supply levels stay rather vague or are limited to rather general statements that the infrastructure provision should be restored as soon as possible after a disruption. Along the same line, practice and policy has

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also struggled to define the ways in which minimum supply is to be prioritized in situations of limited capabilities and resources, i.e. in crises and disaster situations. Lastly, the question of who is – and should – be responsible for the provision of minimum supply remains strikingly open in many respects and contexts.

Yet, while science can and should play a key role in tackling these questions, we argue that none of these questions can and should be resolved in a technocratic manner. Scientific knowledge on, for instance, socio-spatial patterns of vulnerability does not automatically lead to "objective" prescriptions or even recommendations on necessary action, prioritization and responsibility. These aspects are rather need to be tackled and resolved in a wider societal debate that addresses the social contract for risk reduction and shifts the decision-making into the political realm of wider risk governance. In that sense, the agenda ahead is one of transdisciplinary co-production and societal debate, rather than of risk science and critical infrastructure management alone.

6. Conclusion

The analysis presented in this paper has shown that scientists, risk practitioners and policy makers are increasingly concerned about the links between critical infrastructure and disasters. Scientific literature, policy documents, legal frameworks and guidance documents for risk reduction practices therefore engage evermore with the topic of critical infrastructure resilience and its management in crises and disaster situations. However, the links drawn to minimum supply contingencies or the assessment of socially differentiated vulnerability towards CI failure remain to be strikingly weak, if not absent in many contexts. The existing gap between these perspectives is a grave shortcoming as it inhibits a comprehensive understanding of the risks related to critical infrastructure failure and successful disaster risk reduction policies and practices. The paper therefore put forward a framework that helps to decipher the linkages between critical infrastructure resilience, minimum supply and social vulnerability in an inclusive manner, thereby providing guidance for future research agendas and policy as well as practice. However, the analysis also strongly shows that the main challenges might not lie within the technological or managerial questions to be solved, but in the normative, ethical and political questions around the responsibility for and prioritization of minimum supply at the fuzzy interface of state organs, private-sector CI utilities, civil society and affected individuals themselves, the latter of which are more often than not are amongst the weakest, most vulnerable and resource-poor parts of society. Moving the discourse on the responsibility for minimum supply and preventive risk reduction to a stage of more explicit political and societal debate is therefore urgently needed, particularly in view of the increasing levels of disaster risk to be expected in the future.

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Figures

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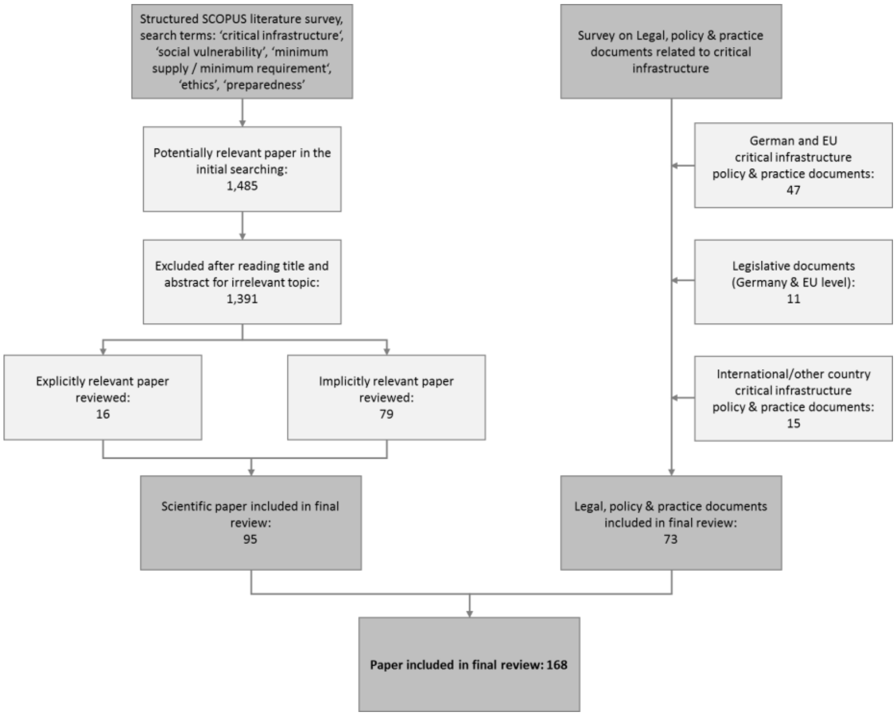

Figure 1: Sampling for the literature review

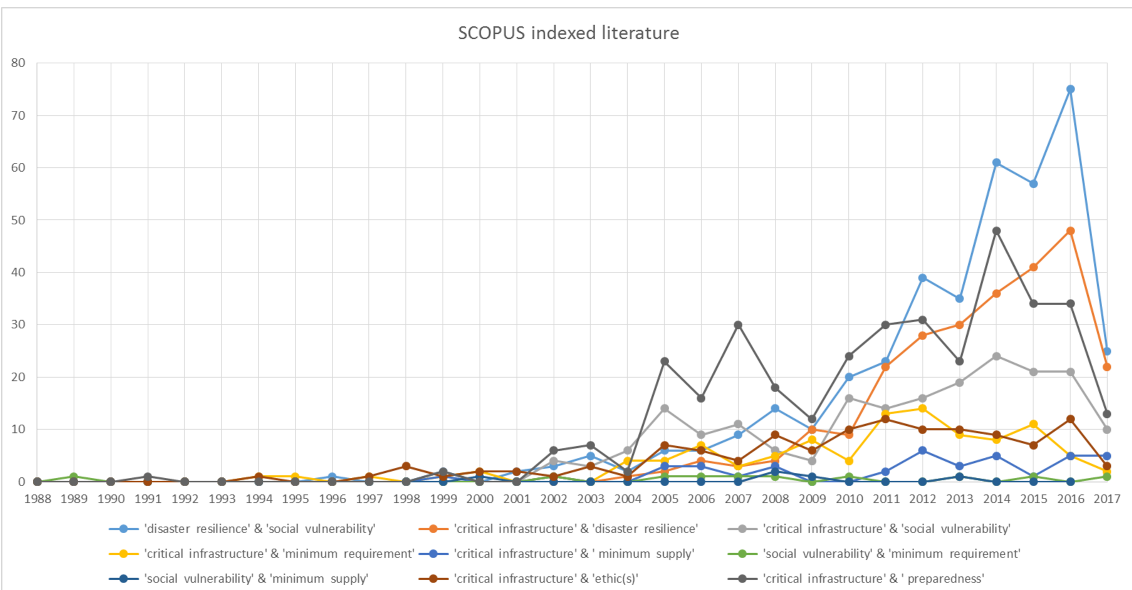

Figure 2: Scientific publications related to critical infrastructure

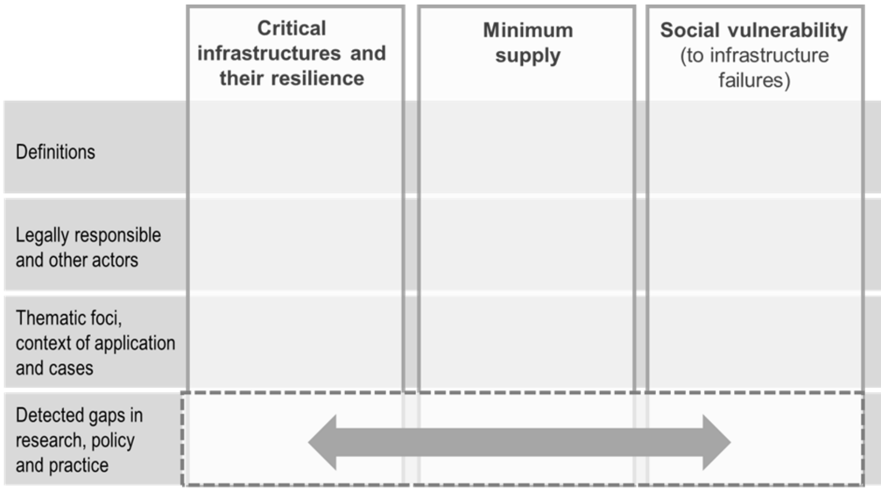

Figure 3: Analysis scheme for both, research and grey literature

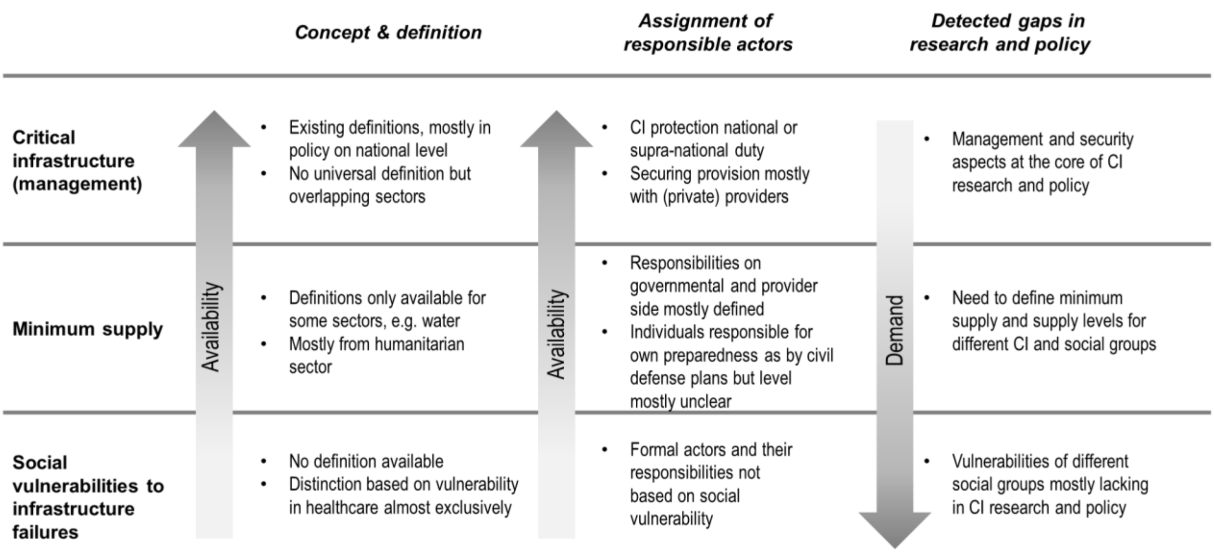

Figure 4: Summary of concepts, actors and backlogs in dealing with critical infrastructure, minimum supply, and social vulnerabilities

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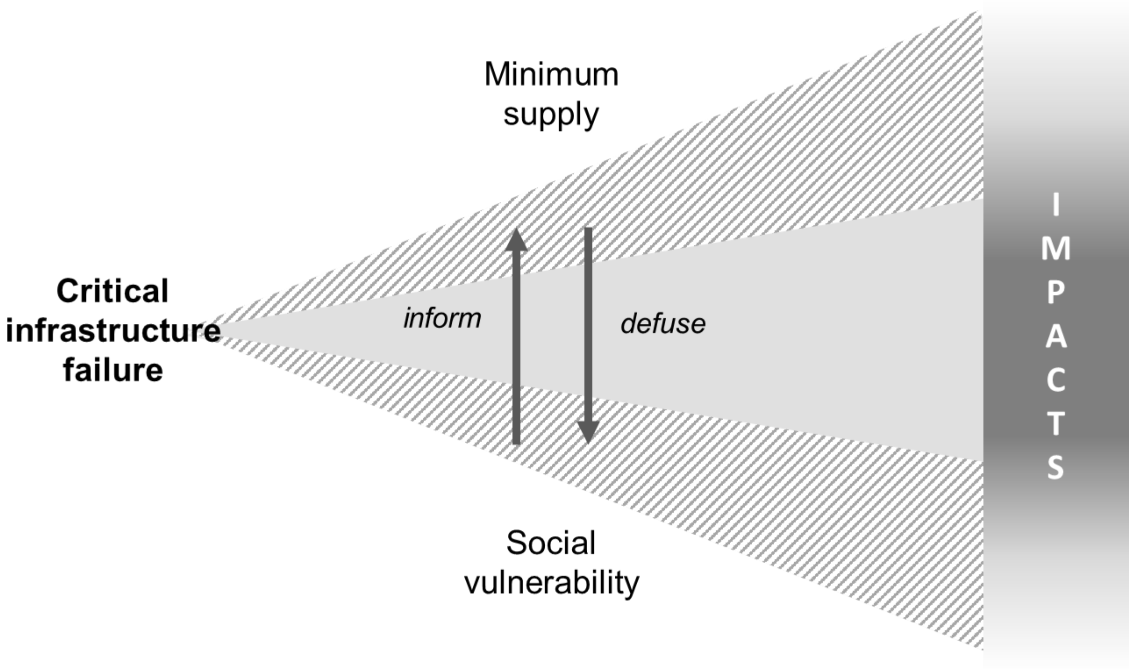

Figure 5: Framework for capturing the relationship between critical infrastructure failure, minimum supply and social vulnerability