Effects of Prolonged Electricity Supply Disruptions on Critical Entities

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Abstract

This study investigates Swedish critical entities (CEs) ability to maintain function during up to three months of electricity supply disruptions. It also examines possible improvement measures, and how contextual cases (grey zone, heightened state of alert, war) influence CEs' ability to maintain function during electricity supply disruptions. Expert elicitation was conducted with experts from eight CEs. The methodological approach provides an easily comparable base measure of critical flow disruption effects on CEs, which can be used for further analyses (e.g. quantifying societal consequences). From the analysis it is concluded that CEs are more vulnerable to outage length (hours/day) than duration (consecutive days with certain outage length). The ability for CEs to maintain function varies significantly and uncertainty of estimates increases with duration. CE function is generally worsened by contextual cases. Many identified improvement measures are CE-specific, but generic categories include improved supply solutions, joint coordination with interdependent actors, and alternatives to diesel auxiliary power. Adequately assigned deployment duties are essential during states of heightened alert and war. It might be timely to capture potential synergies with ongoing expansion of distributed electricity sources (e.g. solar, city-level battery storage facilities). It is concluded that improvement measures should be based on analysis of individual CEs ability to cope with prolonged electricity outages.

Keywords: vital societal function (VSF), critical entity (CE), vital societal entity (VSE), critical infrastructure (CI), critical flow, prolonged outage, electricity supply disruption, preparedness, total defence, civil defence, civil preparedness, crisis preparedness, grey zone, critical entities resilience (CER), hybrid warfare, energy security, societal resilience, cascading effect, dependencies, interdependencies, long-term disruption, power outage, power disruption, consequences, outage, samhällsviktig verksamhet, kritisk infrastruktur, totalförsvar, beredskap

Preface

Written during spring 2023, this thesis equals 30 ECTS and concludes a Master of Science in Engineering, Risk Management and Safety Engineering. It was conceived based on a research grant within AFRY™ recognising gaps on the topic. The thesis was jointly supervised by AFRY's Safety business unit and the Division of Risk Management and Societal Safety, LTH Faculty of Engineering at Lund University.

Although an interesting topic, seeing hazards to electricity supply play out in Ukraine from the stillness of a library desk is enough to wish one's thesis lacked practical application. But as indicated by the thesis, planning and mitigation efforts drastically outperform wishful thinking.

For enabling the exploits of my university time, I extend appreciation to friends and family. I thank Zeth Söderlund and Hamon Hedayatnasab for unrivalled lunch breaks; Erik Kimblad for introducing me to the research grant; Simon Cederholm for consistent encouragement; my mother, father, and especially Johanna, for putting up with unreasonable working hours and too many simultaneous side hustles.

Though anonymised, I express recognition to the participating experts for offering your time and knowledge. For elevating the thesis from a hopeless vortex of unrelated ideas to something worthy of the university logo, I address my gratitude to the supervisors. Tove Raquette, for your valuable support and practical perspectives; Associate Professor Jonas Johansson, for your academic guidance and meticulous answers to questions small and large – anything of use in this thesis is thanks to the two of you.

André Hansson
Lund, May 2023

Effects of Prolonged Electricity Disruptions on Critical Entities

Critical entities are the nervous system of modern society. They maintain vital functions like internet connection and drinking water supply. In this era of power system transformation and rising security threats, critical entities unprepared for prolonged power disruptions risk significant societal impact.

Ongoing transformation of the Swedish power system and uncertainties in European electricity supply[1] have been accompanied by a degraded security situation. The latter includes infrastructure sabotage near Sweden and open attacks on Ukraine's energy apparatus[2]. This emphasises the importance of considering effects from prolonged electricity disruptions. In our increasingly interdependent society, disrupting critical entities such as hospitals or telecommunication operators could entail severe consequences to important societal functions. Analysing how they are affected enables informed mitigation and adaptation. Furthermore, ongoing expansion of Swedish preparedness and total defence[3] brings legal and ethical incentives to address the issue.

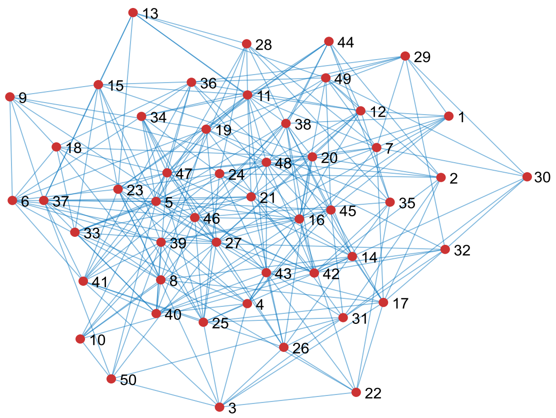

Illustration A. Interconnectedness of modern society visualised as dependencies between 50 critical entities.

Using expert elicitation Hansson[4] has shown that critical entities are vulnerable to outages, but also that consequences are not necessarily worsened in prolonged scenarios. However, function varies substantially between actors, and uncertainty grows as duration is prolonged. It is demonstrated that entities are strained if outages occur combined with contextual factors like grey zone activities or war, where inadequate staffing and supply flows negatively impact function maintained.

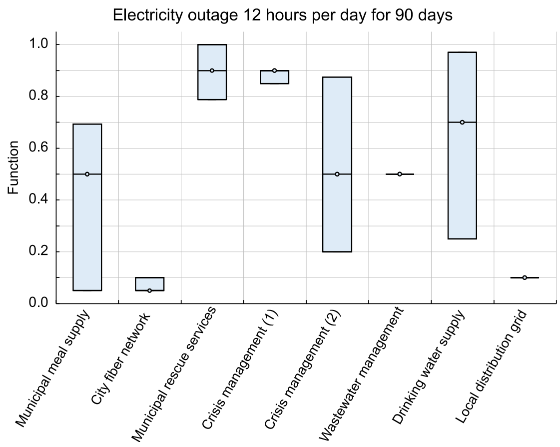

Illustration B. Example of varied function during prolonged outages, where boxes cover plausible intervals and circles mark best assessments[4].

Although this underlines a need for improvement measures tailored to individual entities, common threads include improved supply solutions, joint coordination with interdependent actors, and alternatives to diesel-fuelled auxiliary power. Adequately assigned deployment duties are essential for entities to withstand electricity disruptions during heightened alert and war. Most examined entities relied on diesel auxiliary power. It indicates wide societal dependence on diesel supply, which might be unreliable in times of large-scale disruption. Expansion of intermittent energy sources is sometimes feared to decrease reliability in Swedish power supply – but capitalising on potential synergies, e.g. solar or city-level battery storage facilities for islanding, might be a timely effort to increase critical entities resilience against electricity disruption.

André Hansson, May 2023

[1] Swedish Energy Agency. (2023). *ER2023:07*.
[2] MUST. (2023). *MUST Årsöversikt 2022*. Swedish Armed Forces.
Swedish Security Service. (Nov 2022). *Confirmed sabotage of the Nord Stream gas pipelines*. Retrieved from sakerhetspolisen.se
[3] SOU. (2021:25). *Struktur för ökad motståndskraft*.
[4] Hansson, A. (2023). Effects of Prolonged Electricity Supply Disruptions on Critical Entities. Lund University.

Abbreviations

BCM	business continuity management (kontinuitetshantering)
CE	critical entity (samhällsviktig verksamhet)
CI	critical infrastructure (kritisk infrastruktur)
EU	European Union (Europeiska unionen)
FOI	Swedish Defence Research Agency (Totalförsvarets forskningsinstitut)
IPCC	United Nations Intergovernmental Panel on Climate Change (Förenta nationernas mellanstatliga klimatpanel)
MSB	Swedish Civil Contingencies Agency (Myndigheten för samhällsskydd och beredskap)
MUST	Swedish Military Intelligence and Security Service (Militära underrättelse- och säkerhetstjänsten)
SFS	Swedish Code of Statutes (Svensk författningssamling)
SOU	Swedish Government Official Reports (Statens offentliga utredningar)
UN	United Nations (Förenta nationerna)
UPS	uninterruptible power supply (avbrottsfri kraftförsörjning)

Terminology

The terminology was selected to be coherent with internationally recognised or academically practiced use, while also accommodating concepts used or defined in the Swedish preparedness and total defence context. Some terms are not directly translatable between the two. To minimise ambiguity when interpreting the thesis, the following terminology list is used. Swedish versions within parentheses.

civil preparedness sectors (beredskapssektorer)	ten sectors into which preparedness-related state authorities by law are organised, with the purpose of enabling development of Swedish civil preparedness
critical entity (samhällsviktig verksamhet)	entities providing essential services crucial for the maintenance of vital societal functions (European Commission, 2020; European Council, 2022) an activity, service or infrastructure that maintains or ensures vital societal functions (MSB, 2020) specific operators or facilities within a critical infrastructure (Pursiainen & Kytömaa, 2023)
critical flows (kritiska flöden)	services or products provided to society by critical infrastructures
critical infrastructure (kritisk infrastruktur)	assets or systems providing reliable flows of services or products essential to vital societal functions (European Council, 2008; Executive Order 13010, 1996)
deployment duty (krigsplacering)	position assigned to specific person, which the person by law must serve in during heightened state of alert
vital societal function (samhällsviktig funktion)	a function essential to society's basic needs, values, or security (e.g. the function emergency care is maintained by the critical entities ambulance services, hospital services) – 58 functions have been defined in Sweden to date (MSB, 2023c)
heightened state of alert (höjd beredskap)	can be enacted by the Swedish government, mobilising the Armed Forces and total defence, effectuating laws on deployment duty service, requisition of property, etc.

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1 Introduction

This chapter briefly introduces context, scientific background, aim, and research questions for the thesis. The chapter concludes with a description of scope and limitations.

1.1 General context

Critical entities (CEs) contribute to maintaining vital societal functions, i.e. functions that are essential to society's basic needs, values, or security (European Council, 2022; MSB, 2023c). CEs constitute specific operators or facilities within wider critical infrastructure (CI) sectors (Pursiainen & Kytömaa, 2023). CIs can be viewed as assets or systems that provide reliable flows of services or products essential to the vital societal functions (European Council, 2008). There are significant dependencies between different CIs, meaning one infrastructure requires the flow delivered by another infrastructure to maintain performance. One of the most important CIs is the power system and the electricity it supplies – CEs within all CI sectors are dependent upon it.

The Swedish power system is transforming, e.g. decommissioning nuclear reactors and expanding intermittent electricity sources such as wind and solar – in a time of significant expected changes in electricity use. The change is driven by, among other factors, industrial transition and transport sector electrification. The Swedish Energy Agency (2023) forecasts two- to fourfold increase in industrial use of electricity by year 2050, and large increase in total energy consumption. Simultaneously, already considerable uncertainties related to European electricity supply have been accompanied by a large-scale invasion of Ukraine by Russia. It has included attacks on energy infrastructure (MUST, 2023). Acts of sabotage have been carried out against European CI near Sweden, i.e. the *Nord Stream* pipelines (Swedish Security Service, 2022).

Throughout the past decade, lawmakers have step by step decided to rebuild, renew, and expand Swedish crisis preparedness and total defence capabilities. In that context increasing electricity demand and new types of threats to CIs underline the importance of understanding how CEs are affected by electricity supply disruptions – and how vulnerability can be reduced. The general focus of the thesis was guided by a research grant within AFRY, which recognised gaps in the research on effects of prolonged electricity supply disruptions on CEs in Sweden.

1.2 Scientific background

Consequences from disrupted critical flows are often described as size of the supply disruption, measured for example in MWh for power systems (Chang, 2016). It is rarer that consequences at a wider societal level are considered in risk and vulnerability analyses for CIs, i.e. higher-order consequences arising across society due to dependencies. According to Svegrup et al. (2019) this risks underestimating the total size of consequences, and hence can misguide decisions. According to Hasan and Foliente (2015), direct economic consequences resulting from interruptions in critical flows have been investigated, while other socio-economic consequences have not. A US study was conducted by Esmalian et al. (2021). It examines outage lengths up to 20 days, but only consequences at the household level.

For the Swedish context there are studies on consequences of electricity outages, although often related to shorter durations (Landegren, et al., 2019; The Swedish Energy Markets Inspectorate, 2021). Raquette (2021) examines consequences at the household level in a Swedish municipality for different lengths of interruptions for different critical flows. Sjöstrand et al. (2021) examine 30-day water supply interruptions and their impact on businesses. Some empirical data exists for prolonged electricity supply disruptions in Sweden. For example, there are studies examining a 7-week outage that occurred in 2005 (Johansson, et al., 2006; Guldåker, 2009). Johansson, Svegrup, and Hassel describe in two articles (2016a; 2016b) a method for collecting and structuring data, and a simulation model to capture dependencies between societal entities from a flow perspective. Furthermore, they describe several analyses that can be performed with the model using collected data from Swedish CEs. They demonstrate how such analyses can contribute to increased understanding of interdependencies at a community and societal level, and support decisions regarding risk and vulnerability management at those levels. The time perspective for interruptions of various critical flows ranges from hours up to one year.

These articles exemplify effects of flow disruption on society. But they also underline the need for investigation of prolonged electricity supply disruption effects on CEs in Sweden – especially in a changing security context which previous literature has had limited focus on. A specific study on the ability of Swedish CEs to handle electricity supply disruptions lasting three months, and exploring varying contextual factors, has not been previously addressed. Given that at least three months of severe disruptions is a required design basis for Swedish total defence planning, further investigation is justified.

1.3 Aim of thesis

The overarching purpose of this thesis is contributing to more informed decisions in the improvement of resilience for CEs, particularly related to Swedish total defence capabilities.

Guided by that purpose, the aim of this thesis is to increase the knowledge of how prolonged electricity supply disruptions affect CEs and how the consequences of such disruptions can be minimised.

1.4 Research questions

To fulfil the aim, a set of research questions were defined:

1) How are CEs affected by up to three months of electricity supply disruptions, and how can this be measured?
2) How does ability to maintain function differ if the electricity supply disruptions occur during three contexts: grey zone, heightened state of alert, and war?
3) How does ability to maintain function differ between CEs affected by up to three months of electricity supply disruptions?
4) How can CEs improve their ability to cope with up to three months of electricity supply disruptions?

The questions are answered delimited to a certain number of selected CEs and only within the scope described in 1.5.

1.5 Scope & limitations

The scope was limited to actors in southern Sweden. For reasons of anonymity and sensitive information, specific organisations, experts, and geographical locations are only described in general terms. Eight CEs of various types were examined. This limited sample leads to constraints related to generalisability and validity as discussed in 2.2.3, 5.2, 5.3.

The duration of electricity supply disruptions examined is limited to a maximum of three months for quantitative data. Longer durations were only addressed through qualitative data. It was deemed likely that most interesting results would emerge at or before the three-month mark, because it gives time both for long-term adverse effects, and adaptive measures. However, it must be considered that for durations exceeding 3 months, other effects than those shown in this thesis might appear.

Gathering of data was limited to two primary methods: a semi-systematic literature study, and expert elicitation. There are other possible methods available, e.g. empirical methods or modelling and simulation approaches. The choice of methods was based on the nature of the research questions, expected types and availability of data, available time and resources for the study, and advice from the supervisors.

Regarding the literature study, no full systematic review aimed at identifying as much literature as possible was conducted. This was due to limited time and resources. Instead, a semi-systematically identified selection of literature was reviewed (see 2.1). The expert elicitation was limited to experts from a selection of CEs and the quantitative data were limited to certain outage scenarios and target variables (see 2.2).

Dependencies and cascading effects are not directly accounted for in the quantitative data. The quantitative results only account for direct effects of electricity supply disruptions for a given CE. Dependencies and cascading effects are discussed at a general level and examined qualitatively for specific CEs.

2 Methodology

Primary methods used were expert elicitation and a semi-systematic literature study. Expert elicitation was done using two secondary methods: a survey study and an interview study. Scenario and target variable design are detailed. This chapter aims to enable reproducibility, and future evaluation of the thesis' credibility (Backman, 2008).

2.1 Literature study

In an initial phase, literature was identified and used as a starting point for relevant theory, background, and formulation of research questions. Academic literature was prioritised, although some non-academic sources were also used. Regarding non-academic sources, grey literature was premiered. Grey literature consists of articles, reports, and investigations, authored without involvement of commercial actors (Schöpfel, 2010). The literature identification was partly inspired by scoping study methodology as described by Arksey and O'Malley (2005), but the applied approach was less systematic and more iterative. The general approach was also informed by the mixed-methods review as presented by Harden (2010), to promote synthesis of qualitative and quantitative data. This generally entails one search for each type of data, and that at least one search method is systematic (Grant & Booth, 2009).

Most academic literature was found using two search engines: Google Scholar and LUBsearch. To ensure high quality and correct scope in identified literature, settings were selected according to the following criteria, to the extent possible for each search engine:

- Only peer-reviewed articles, as advocated by Höst et al. (2006).
- Only articles in English or Swedish.
- Only articles containing relevant keywords in the abstract.
- AND, OR, and * (word ending variation) options were used to relate keywords in different combinations.
- If the scope of a search result was deemed too big or not relevant enough, settings were changed to show only articles containing keywords in the title.

Keywords were combined in a semi-systematic and iterative process over time. The main keywords used are listed below (Swedish in parenthesis):

- critical infrastructure (kritisk infrastruktur)
- resilience (resiliens)
- critical flow (kritiskt flöde)

- electricity supply (elförsörjning)
- disruption (störning)
- outage (avbrott)
- preparedness (beredskap)
- civil defence (civilförsvar)
- total defence (totalförsvar)
- power system (kraftsystem)
- critical entity (samhällsviktig verksamhet)
- consequence (konsekvens)
- grey zone (gråzon)
- interdependency (samberoende)
- continuity management (kontinuitetshantering).

The grey literature was found using the regular Google search engine. In addition, some literature (academic as well as grey) was identified by direct reference from the thesis advisors or by inquiring officials. Lastly, further literature was identified in the references of already used literature.

Following the initial phase, identification and use of literature continued iteratively throughout the thesis process. It was used to define a conceptual foundation for the thesis. It also augmented the expert elicitation and related analysis.

2.2 Expert elicitation

Little empirical data from prolonged electricity supply disruptions exist for Sweden, since few such disruptions have occurred. There is one example of a 7-week power outage in relatively modern times (Johansson, et al., 2006; Guldåker, 2009), but more tangible results related to CEs subject to prolonged disruptions are hard found. It was also hard found for other countries, especially in the context of grey zone activities and war. Even though such situations have played out it requires well-curated data concerning effects on CEs for it to be useful in this thesis. In addition, differences between societies could complicate extrapolation of such data from one specific context to another.

Expert elicitation entails a range of frameworks and methods to elicit as accurate expert judgment as possible, minimising biases and overconfidence. Expert elicitation should be based on best available research and used only if '[…] the state of knowledge will remain insufficient to support timely informed assessment and decision making' without it (Morgan, 2014). Because total defence and continuity management planning requires proactive preparation, and the state of knowledge was deemed insufficient, it was decided to use expert elicitation.

2.2.1 General approach

Experts are human, hence total elimination of cognitive bias and overconfidence is not possible. At best one can strive to minimise negative impacts of those phenomena on the accuracy of judgments. Acknowledging that and designing elicitation procedures aimed at such minimisation are important (Morgan, 2014). In addition, as Morgan notes, it is important to remember '[…] science is not a matter of majority vote' – meaning aggregation of different expert's judgments is not necessarily closer to reality than one outlier judgment. Still, empirical studies indicate that aggregated judgments have higher probability of being accurate (Budescu & Chen, 2015; Atanasov, et al., 2017; Tetlock, et al., 2017). Human inadequacies for assessment have been at the centre of much expert elicitation literature, to a degree Kynn (2008) considers a 'heuristics and biases' bias. Kynn highlights that recent literature refutes many older ideas. It shows that experts can be well calibrated to the task and that expert elicitation accuracy can be improved through appropriate processes, framing, questioning, and training.

To accommodate such bias minimisation and accuracy improvement, frameworks were reviewed and synthesised. The general procedure guide by Cooke and Goossens (2004) inspired the approach. Avoiding aggregation as referenced to Morgan above, performance measures requiring weighting of experts were left out. This relinquished the need for an assumption required in a 'Classical model' or Bayesian models – that future expert performance can be judged on past performance – thus reducing epistemological baggage. But as mentioned, aggregation measures do often increase the probability for accurate assessment. Hence, the premier merit of avoiding aggregation was pragmatic rather than scientific in character. It removed need for several different experts on the same specific CEs, and in many cases only one suitable expert existed for a given CE and its examined function. The four-step elicitation format of Hemming et al. (2017) was incorporated. Also included was their idea of giving experts opportunity to adjust their initial assessments during a follow-up interaction, after having time for hindsight thoughts and being exposed to other experts' assessments. This was achieved using a survey and following up with an interview where survey data could be adjusted by the expert. Surveys and interviews were conducted in Swedish.

A chronological procedure was outlined and followed:

(1) Define case structure
   a. Purpose, aim, and scope of expert elicitation (1.2-1.5)
   b. Necessary knowledge of background and concepts (3.1-3.6)

(2) Define target variables and scenarios (2.2.2 and A)
   a. Choose model variables to be assessed by experts

b. Establish scenarios for variable assessment

(3) Identify and select experts (2.2.3)
   a. Identify potential experts
   b. Determine availability of potential experts
   c. Select combination of experts suited to fulfil (1) and (2)

(4) Define elicitation format documents
   a. Survey (C)
      i. Create survey to accommodate (2)
      ii. Create preparatory information and instructions for the survey
      iii. Test survey materials on external expert and collect feedback
      iv. Adjust materials based on feedback
   b. Interview (B)
      i. Create interview guide to follow up survey and accommodate (2)
      ii. Create preparatory information for the interview
      iii. Test interview materials on external expert and collect feedback
      iv. Adjust materials based on feedback

(5) Conduct expert elicitation survey (2.2.4)
   a. Send preparatory information and instructions to experts
   b. Send survey to experts and await results
   c. Initial analysis of survey results

(6) Conduct expert elicitation interviews (2.2.5)
   a. Send preparatory information and instructions to experts, including selected survey assessments of other experts
   b. Conduct interview according to interview guide

(7) Post-elicitation analysis (4-6)
   a. Data processing
      i. Clean-up (ensure anonymity, arrange in user-friendly interface, verify interpretations or possible formal errors with experts, remove formal errors)
      ii. Standardise intervals
      iii. Aggregate and visualise
   b. Analyse, discuss, draw conclusions

2.2.2 Target variables & scenario design

Informed by the approach of Chang et al. (2013) it was decided that point estimates of resilience measured in terms of CE service disruption were suitable to answer the research questions. More specifically, it was measured as fraction of normal function deemed possible to uphold given a certain electricity outage scenario. 'Function' here means the critical flow of services provided by a CE (further detailed in 3.1 and Figure 3). 'Normal' is the level of function usually maintained without presence of significant disruptions. It is conceivable that a CE in certain conditions could perform better than normally. In other words, 100% of normal function is not necessarily an upper limit of performance. For the sake of example: normal function of a port could be 100 containers processed per day. However, it could be possible to process 120 containers per day if abnormal conditions applied, e.g. calling in extra personnel and skipping safety procedures. For this port, disruption effects would be measured as fraction of normal function (100 containers processed per day) maintained.

To assess function the four-step elicitation by Hemming et al. (2017) was used, meaning for each scenario three separate point estimates (lowest plausible, highest plausible, best assessment) were elicited. For each such interval the experts also had to assess their confidence levels (between 0-100%) that the elicited interval captures the 'real' value – referring to the expected future outcome should scenario conditions be realised. Speaking of 'real' values for a yet unrealised future is laden with assumptions this paper does not attempt to justify. Instead, confidence levels are viewed as subjective probabilities interpreted as the expert's degree of belief in the event occurring (Lindley, 2000; Aven, 2020). Intervals were standardised to 90% confidence level using linear extrapolation (Adams-Hosking, et al., 2016; Bedford & Cooke, 2001). This was done to enable comparison of results, and to reduce overconfidence in expert interval judgments (Speirs-Bridge, et al., 2010).

Outage scenarios were determined as combinations of *length* (number of hours of electricity outage per day), and *duration* (number of consecutive days with the given electricity outage lengths). Outage lengths were set as short (2 hours/day), medium (12 hours/day), and long (24 hours/day). Scenario durations were set to 7 days, 30 days, and 90 days. In the elicitation process it was clarified that no other disruptions occurred simultaneously and that potential interdependencies or cascading effects (detailed in 3.2) should not be accounted for. For the outage scenarios it was clarified that outages were to be considered unplanned (i.e. no information regarding occurrence of outages available for the CE in advance of the outages). In the survey, this was supplemented by asking how assessments would change if outages were instead planned (i.e. advance information regarding outages available to the CE). Three contextual cases (grey zone, heightened state of alert, war) based on Swedish Defence Research Agency (FOI) cases to support total defence planning (2014; 2018) were used for qualitative questions in the interview. Using those cases aimed to cover how wider contextual factors related to a worsened security situation could impact the quantitative assessments. Detailed outage scenarios and contextual cases are presented in A.

2.2.3 Expert selection

Selection criteria were inspired by Cooke and Goossens (2004). Specifically, the following criteria guided selection:

- The person works at a CE maintaining a specific function (critical flow) contributing to vital societal functions.
- The person is deemed an expert on the CE represented, and the specific function to be examined.
- The specific CE is in close proximity to end users (e.g. local supermarket rather than national food authority).

Selection of experts aimed to represent as many CEs as possible, and to cover at least four civil preparedness sectors (sectors are detailed in 3.6 and E). Online search engines, CE websites, and existing personal networks were leveraged to identify potential experts. Ultimately, selection was limited by potential experts' interest in participation, and their availability with respect to time limitations in the thesis process. Deeming whether a person was an expert was done in two steps. First, the CE was provided detailed information of the thesis including its elicitation process and asked to refer its most suitable employee to answer for a specific function. Second, the elicitor (same as the author in this case) ensured that this employee personally took part of the detailed information about the elicitation process. The elicitor also asked verifying questions related to this information and the specific function represented to ensure that the person was suitable for elicitation. Some referred employees were found unsuitable, and thus were not selected for elicitation.

Experts are listed in Table 1. Some CEs contributed to several specific functions (e.g. operating fiber network and district heating). In these cases, one function was singled out, and all elicitation from that expert concerned only that function.

Table 1. Participating experts.

CE type	Expert position	Specific function examined
Municipal meal production	Meal Strategist	Municipal meal supply
Fiber network operator	Security Officer	City fiber network
Rescue services	Operations Chief	Municipal rescue services

Municipal management (1)	Preparedness and Safety Coordinator	Municipal crisis management (1)
Municipal management (2)	Crisis Preparedness Coordinator	Municipal crisis management (2)
Wastewater utilities	Security Officer	Wastewater management
Drinking water utilities	Plant Engineer	Drinking water supply
Electricity distribution operator	Electrical Installations Manager	Local distribution grid

In total eight experts from a varied set of CEs participated. As already described, this thesis avoids aggregation of results from different experts on the same specific CEs, and instead uses one expert for each respective CE examined. Approximately 15 more experts representing several CEs (e.g. public transportation, hospital, district heating, port, dairy production, supermarket chain central warehouse) were engaged with, but were either uninterested or could not participate given the timeframe.

2.2.4 Expert survey

The expert survey was conducted using Sunet's Survey® platform (see C). Questions were divided by scenario into separate pages, making it clearer to the responding expert (Kelley, et al., 2003). The survey was designed to elicit assessments of the base outage scenarios. These questions were closed with pre-coded alternatives. Pre-coded closed questions were deemed suitable given the base scenario design and target variables. Additionally, Kelley et al. (2003) suggest it simplifies analysis and lessens burden on the respondent. This was supplemented by a qualitative question on how assessments might be affected if outages were planned or unplanned, also with closed pre-coded alternatives. It concluded with open text questions on assumptions and additional information. The recommendations of Kynn (2008) related to minimising biases, overconfidence, and fallacies, guided question formulation. The general rationale of the thesis and its methodology, including the expert elicitation survey and interview, was provided in written form to all experts before the survey was sent out. Anonymised survey assessments were curated for sharing with other experts preceding their respective interviews.

2.2.5 Expert interview

A semi-structured interview approach was used. This type of interview allows follow-up queries to open-ended questions (Adams, 2015), deemed valuable for qualitative inquiries. Preceding each interview the experts received preparatory material to reduce misunderstanding and enable accurate elicitation. It included the contextual cases (see A). It also included the selected assessments made by themselves and other experts, that they were to review before having the chance to adjust their own assessments. Finally, it included instructions to:

- Read provided materials carefully.
- Consider their own assessments and whether something should be changed, especially in relation to the stated scenario conditions, and assumptions that they had made.

The interviews were conducted digitally via Zoom®. To minimise fatigue, interviews were planned for a length of one hour, as recommended by Adams (2015). Zoom's built-in recording function and a voice recorder on a separate device were used. After the expert's approval, recording started and the semi-structured interview was conducted according to an interview guide (see B). It started with an opportunity for the expert to adjust any assessment the expert had made in the survey. As Chang et al. (2013) note, this validation approach is based on re-asking the same questions rather than convergence achieved asking for the same assessment with different question formulations. The interview guide was designed based on the approach of Adams (2015). Again, Kynn's recommendations (2008) guided question formulation.

2.2.6 Confidence level standardisation

To enable useful comparison of results from different CEs and experts, interval assessments were standardised to the same confidence level Γ_S using linear extrapolation. 'Interval assessments' refer to the spaces between highest and lowest plausible assessments by an expert for a given scenario. Partly inspired by Hemming et al. (2017) it was decided to set the standardised level of confidence Γ_S to 90%. It is a reasonably high level, implying data can be used for further analysis with relative confidence. However, it is still dependent on the accuracy of initial assessments. 90% was also low enough to minimise the number of interval sizes so large that useful analysis is complicated (e.g. an interval ranging from 1% to 99% function). A wide interval can itself be useful information as it might indicate large aleatoric uncertainty (e.g. system variability), or large epistemic uncertainty (e.g. knowledge of potential outcomes is limited). Directly identifying which it is would require a more complicated survey, which might confound assessments. Instead, details from the interviews were used to inform the distinction between aleatoric and epistemic uncertainty. Here it must be noted that some unknowns might be unknown, i.e. epistemic uncertainty can exist even if not indicated by the expert or the assessments. Furthermore, pre-standardisation assessments did not include such wide intervals as discussed above. It was assumed unstandardised expert assessments were more indicative of reality than a very wide interval following standardisation to very high confidence, e.g. 99%. Even for a non-expert it would not be unreasonable to assume with 99.9% confidence that function would be between 0% and 100% – but it would not be very useful information for practical purposes. Either way, best assessment remains unchanged by confidence level standardisation and is arguably the most interesting parameter.

Moreover, it was assumed function could not exceed 100% or fall below 0%. The variables specify fraction of normally delivered function from the *specific* CE. So, by definition it cannot be lower than 0%. Exceeding 100% is theoretically possible, since changed conditions might enable an organisation to perform better than normally. However, it was assumed nothing in the outage scenarios improved performance of examined CEs. Based on pre-standardisation assessments and discussions during interviews it was assumed disruptions had only debilitating effects on function, and thus that 100% could not be exceeded.

The linear extrapolation used for standardisation (Adams-Hosking, et al., 2016; Bedford & Cooke, 2001) is given by

$$\lambda_{\Gamma_S} = \phi - \left(\left(\phi - \lambda_{\Gamma_A} \right) \times \left(\frac{\Gamma_S}{\Gamma_A} \right) \right) \quad \text{(Eq. 1)}$$

and

$$\Theta_{\Gamma_S} = \phi + \left(\left(\Theta_{\Gamma_A} - \phi \right) \times \left(\frac{\Gamma_S}{\Gamma_A} \right) \right) \quad \text{(Eq. 2)}$$

where ϕ = best assessment,

λ_{Γ_A} = lowest plausible assessed,

λ_{Γ_S} = lowest plausible standardised,

Θ_{Γ_A} = highest plausible assessed,

Θ_{Γ_S} = highest plausible standardised,

Γ_A = level of confidence assessed,

Γ_S = level of confidence standardised to.

Standardised values were truncated at 0 and 1 using Microsoft Excel® functions in the two following ways: MAX(0;MIN(1; λ_{Γ_S})) and MAX(0;MIN(1; Θ_{Γ_S})).

3 Conceptual foundation

This chapter presents a foundational background, explaining the theoretical context and how specific concepts are used in the thesis.

3.1 CE, CI & critical flow

The functionality of modern society is dependent on critical flows. Critical flows involve the infrastructures, dependencies, priorities, and relationships that link actors, sectors, and levels of decision-making in a normally functioning society (Johansson, et al., 2017). Examples of critical flows are the transport of goods, supply of food, medicines, water, and electricity. More specifically, critical flows can be understood as the services provided to society by CIs (Lee II, et al., 2007; Zio & Sansavini, 2011; Williams, 2021).

Simply put, CIs are infrastructures that are critical to some function or value considered important. The CI concept appears sprung from the late 1980's or early 1990's and is best understood in an international context. Assigned its first formal definition by the United States, a presidential executive order describes:

> Certain national infrastructures are so vital that their incapacity or destruction would have a debilitating impact on the defense or economic security of the United States. These critical infrastructures include telecommunications, electrical power systems, gas and oil storage and transportation, banking and finance, transportation, water supply systems, emergency services (including medical, police, fire, and rescue), and continuity of government. (Executive Order 13010, 1996).

Continuing in the United States, infrastructures in general have been defined as:

> The framework of interdependent networks and systems comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services essential to the defense and economic security of the United States, the smooth functioning of government at all levels, and society as a whole. (President's Commission on Critical Infrastructure Protection, 1997).

In the EU, CIs have been described as:

> […] an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions. (European Council, 2008).

Many uses of CI have often referred to technical infrastructure. That would constitute one part of the Swedish concept 'samhällsviktig verksamhet' (eng. 'vital societal entity'), stemming from Swedish implementation of the EU directive

2008/114/EC on CIs (European Council, 2008; MSB, 2020). 'Samhällsviktig verksamhet' is here equated with the European concept of CE, recently introduced in the EU directive 2022/2557 on CE resilience replacing the directive on CIs (European Council, 2022). It entails entities providing essential services crucial for the maintenance of vital societal functions (European Commission, 2020). The focus and level of analysis are shifted from wider CI sectors toward specific operators and facilities within CIs (Pursiainen & Kytömaa, 2023). In the Swedish context CE has been defined as an activity, service, or infrastructure that maintains or ensures vital societal functions. For example, the function of emergency medical care is maintained by the CEs ambulance services, hospitals, and others. Additional examples of CEs are fire and rescue services, water utility companies, and energy producers (MSB, 2021a).

Both the EU and Swedish definition leave room for interpretation and ambiguity, despite general intentions being clear. It was a deliberate choice to equate them in this thesis, to promote unitary terminology and contribute to convergence between the definitions.

3.2 Dependencies & cascading effects

There are dependencies between different CEs and CIs, and hence the flows or functions that they maintain. Rinaldi et al. (2001) define infrastructure dependency as a '[…] linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other.' When there is mutual dependency, i.e. each of two systems is dependent upon the other, it is called an interdependency. Dependencies can be categorised into various types, see e.g. Rinaldi et al. (2001) or Johansson and Hassel (2010). Here three types are considered:

- functional (e.g. railway and telecom dependence on electricity supply)
- geographical (e.g. co-location on a bridge of railway, road, electricity, water)
- logical (e.g. changing transport mode from railway to road, if rail is affected).

Many dependencies are human-mediated, where the role of humans is at least twofold (Barrett, et al., 2012): as consumers of the provided function and as operators, managers, and policy makers for the infrastructure.

To properly identify, understand, and analyse interdependencies, there are several dimensions to account for. For CIs specifically, Rinaldi et al. (2001) advocate the dimensions in Figure 1. The areas included indicate that successfully accounting for all aspects of interdependency is hard and might be impractical in many situations.

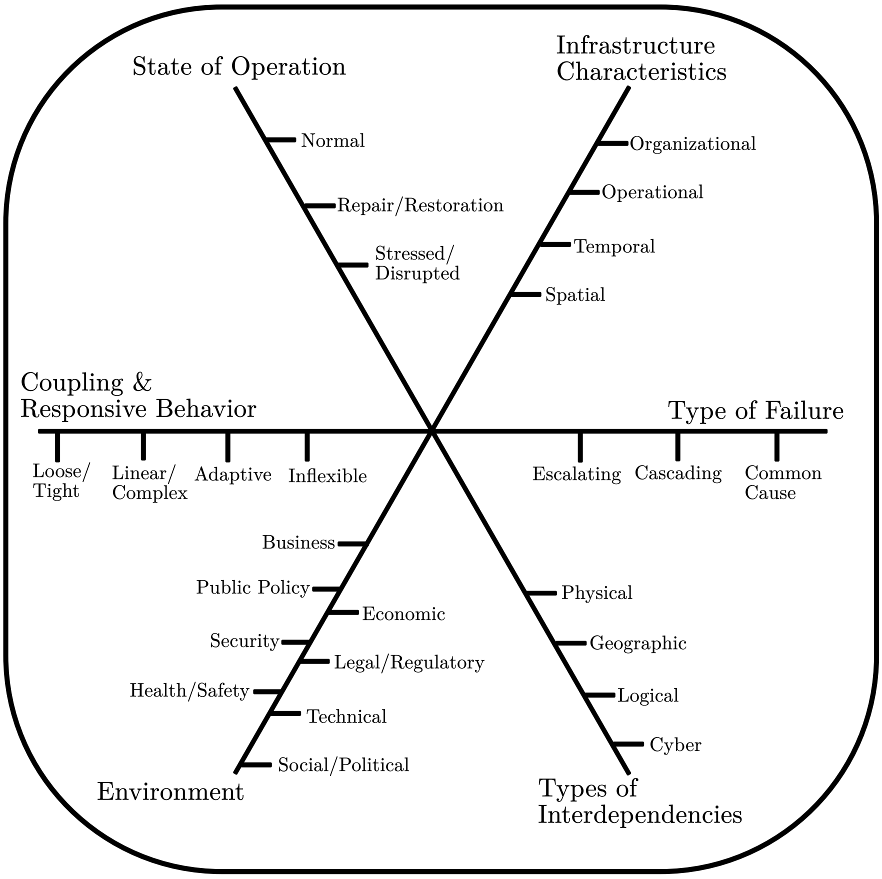

Figure 1. Dimensions entailed in infrastructure interdependencies. Redesigned based on a figure by Rinaldi et al. (2001).

Figure 2 is a visualisation of dependency relations and their importance for critical flows. It is a simplified model in which boxes represent specific functions maintained by different societal entities. Arrows represent direction of flows, and thereby dependence of one upon the other. If a function is disrupted, a propagation of disruptive effects follows the arrows and impacts dependent functions. This is often called *cascading effects* and *domino effects.* 'Cascading effects' mean that consequences are traversing from one system to another due to (inter)dependencies. They are complex, multi-dimensional and evolve over time (Pescaroli & Alexander, 2015). 'Domino effects' usually refers to consequences spreading within one system, such as sequential power lines tripping due to overload. (Inter)dependencies are the key enabler of cascading effects (Johansson & Hassel, 2010).

In Figure 2 an electricity supply disruption would affect the ability of several CEs to maintain their function. In the second order, impacted flow deliveries would propagate from directly affected CEs to those dependent upon it. For example, if examining effects of electricity supply disruptions on the emergency room's ability to deliver its services, accounting only for the disrupted electricity flow risks underestimating total impact.

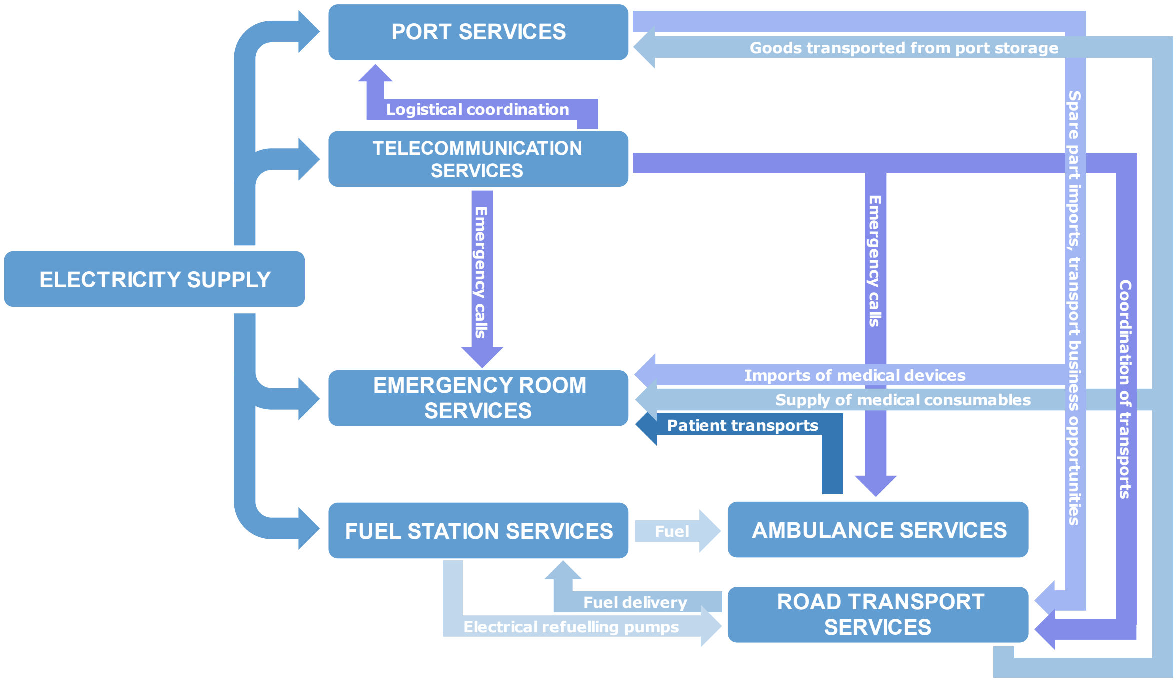

Figure 2. Simplified model of possible dependency relations between functions maintained by different CEs.

The importance of accounting for interdependencies and cascading effects is highlighted by Svegrup et al. (2019), showing that higher-order societal consequences due to electricity supply disruptions can be twice the extent of first-order consequences. In addition, interdependencies give rise to cross-scale challenges for achieving resilient operation of infrastructure systems (Cedergren, et al., 2018). Chang et al. (2013) have further demonstrated the vital importance of accounting for dependencies, but also the difficulty in doing so.

3.3 Resilience, critical flow disruptions & BCM

In the recent decade, focus has shifted from a protection perspective to a resilience perspective where the aim is to create resilient systems, rather than directly protecting infrastructures and preventing any disruption to critical flows (Pursiainen & Kytömaa, 2023). A resilience approach can start from the assumption that disruptions will occur and adapt the system to minimise negative effects (Almoghathawi, et al., 2019). The EU directive 2022/2557 on CE resilience underlines the need for resilience perspectives and aims to unify member state actions related to infrastructure resilience. The resilience perspective might lead to better performing systems compared to other approaches, e.g. focusing only on protection measures. It might allow more holistic and pragmatic considerations accounting for complexity, along with sustainable design and operation (Labaka, et al., 2016; Sonesson, et al., 2021).

Resilience is an idea with different conceptualisations for different settings. Generally, resilience can be said to mean the ability of a system to handle stress and disruptions throughout its existence, sustainably maintaining an acceptable level of performance. Another way to understand it is as the capacity of a system to adapt to changing conditions without unacceptable loss of function or form. For resilience engineering specifically, Woods (2015) presents four outlooks on the concept. He groups the conceptual approach to resilience into the following:

- resilience as *rebound from trauma and return to equilibrium*
- resilience as a *synonym for robustness*
- resilience as the *opposite of brittleness* (or so-called *graceful extensibility*)
- resilience as *sustained adaptability.*

For the topic of this thesis, resilience as robustness as well as rebound and return are relevant. For prolonged scenario durations and qualitative parts of the thesis, resilience understood as sustained adaptability is to some degree relevant. Robustness can be thought of as the ability to withstand a disruption; a threshold of stress below which performance is unaffected, or a measure of how much function is maintained given some disruption. Rebound and return can be thought of as 'bouncing back' to normal performance levels after a temporary decrease due to some disruption. According to Becker (2014), one way to view society or complex parts thereof, such as a CE, is as a *human-environment system.* Compared to others, e.g. the *complex adaptive systems* approach, it has the advantage of encompassing the crucial proactive qualities of human anticipation and learning. Such an approach is fitting to the context of preparedness planning and business continuity management (BCM). Preparedness and BCM can enable mitigation and recovery. Resilience of a specific infrastructure system (e.g. a CE) in terms of function delivered is visualised in Figure 3, including mitigation and recovery effects. In this simplified visualisation, a disruption limited in time causes decrease in function.

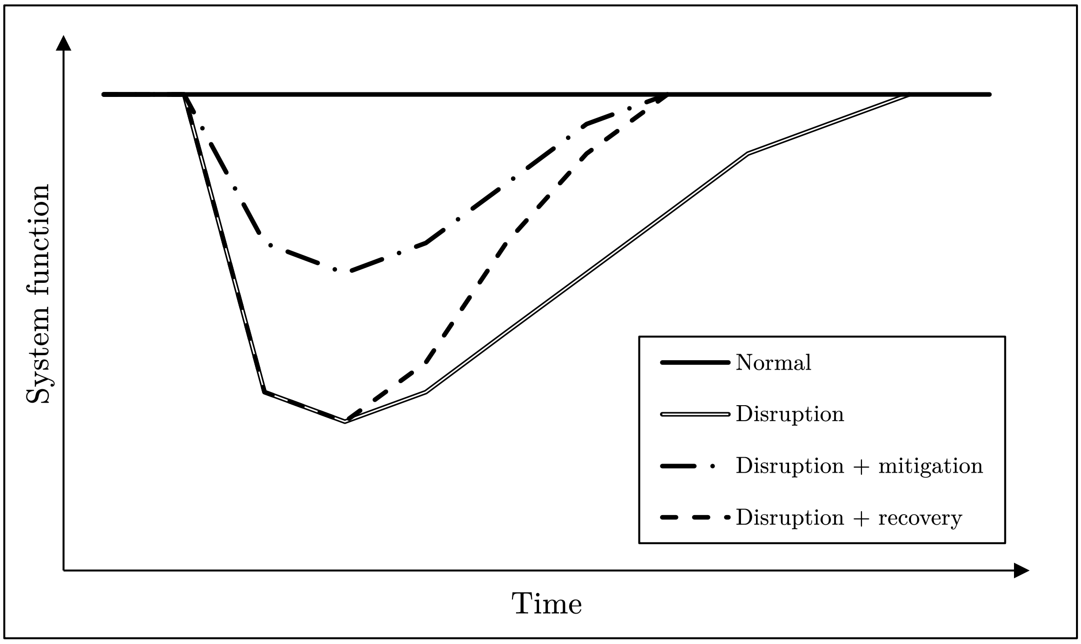

Figure 3. Schematic representation of an infrastructure system's resilience, inspired by Bruneau et al. (2003) and McDaniels et al. (2007).

Many CEs risk far-reaching consequences if the delivery of a critical flow that they depend on fails. Some factors, such as increased societal dependence on these flows and increased complexity, suggest that consequences of disrupted flows may be even greater in the future (Chang, 2016). Disruption of critical flows might be caused by numerous hazards. One useful categorisation presented by Wang et al. (2013) is random hazards (e.g. aging failures), deliberate hazards (e.g. intelligent attacks), and natural events (e.g. earthquakes).

Furthermore, trends such as increased network density, globalisation, frugal resource use, and increased complexity will impact systems to a point of instability, where failures will occur sooner or later (Helbing, 2013). In addition, the UN Intergovernmental Panel on Climate Change (IPCC) notes possibly increased impact on infrastructures due to climate change and its effects (2014). Shifting perspectives from striving for 'fail-safe' to 'fail-to-safe' systems has been mentioned by Ahern (2011) among others. This further indicates the relevance of employing a resilience perspective when approaching issues of critical flow disruption. Some of these issues could be addressed with well-adapted BCM.

BCM is understood here as a plan and process to maintain the organisation's operations at a minimum 'tolerable' level in the event of various disruptions. BCM has a proactive focus and generally concerns specific organisations. If the critical flow of electricity is disrupted, BCM aims for quicker recovery from, and mitigation of, consequences of disruption. Some activities included in BCM are (MSB, 2022a):

- mapping of vital activities and processes
- identifying resource dependencies

- establishing acceptable downtimes for the provided function
- implementing measures to reduce risk of disruption
- creating plans to manage disruptions that still can arise.

Thus, BCM can be used to assess and manage to what degree a CE is impacted by a critical flow disruption.

Additional background on critical flow disruption is described in 1.2.

3.4 Electricity supply disruptions

Almost all registered electricity supply disruptions in Sweden are due to natural events, human error, and the like (Johansson, et al., 2018). However, the greatest external threats to Swedish national electricity supply are cyber-attacks, espionage, and other intelligence gathering activities (Svenska kraftnät, 2018). This highlights the importance of considering deliberate hazards. For empirical data covering 2006-2016 only 5% of transmission system failures led to loss of electricity supply, because of system redundancy and spare capacity. In contrast, for data covering 2005-2015 up to 99.25% of distribution system failures affected at least one end user (Johansson, et al., 2018). This indicates that almost all distribution system failures are highly likely to lead to supply disruptions for end users, including CEs. As for the transmission system, a high degree of redundancy is implied. It is possible that realisation of certain deliberate attacks may challenge this redundancy. Significant disruptions for many end users might occur if the transmission system is affected, e.g. like the large-scale blackout in 2003 leaving southern Sweden and eastern Denmark without electricity supply (Andersson, et al., 2005; Larsson & Danell, 2006).

Apart from grey zone issues including cyber-attacks, sabotage, and the like, there are now in Ukraine concrete examples of what the power system, and as a result the electricity supply, can be subject to during war. In the case of Ukraine months of recurring long-range missile attacks against critical components in the power system have occurred (Butenko, et al., 2022; Matuszak, 2023). A relevant observation is that so far it seems not to have led to a national blackout, but mainly controlled and local rotating power outages between two and six hours long (Visit Ukraine, 2022; Blinov & Djankov, 2022).

To counteract severe consequences in Sweden if electricity production is limited in relation to demand, the *Styrel* system has been developed. Styrel is a systematic way of identifying and prioritising vital electricity end users during a short-term electricity shortage, allowing manual disconnection of parts of the grid (Swedish Energy Agency, 2018). Styrel is not designed to handle sabotage or destroyed components. It is intended to allow prioritisation of electricity distribution to specific users in the event of a power shortage. This might mean that electricity based on available power is prioritised to CEs but does not guarantee continuous electricity supply. It could entail rotating power outages (SFS, 2013:282), not unlike those seen in Ukraine. It is conceivable that Styrel could play a mitigating role if individual components, nodes, or producers within the power system are destroyed, for example by an antagonistic actor. However, as already mentioned, it is not the intended purpose of the system and its usability in such a scenario requires further investigation.

FOI (2014) has published four cases of societal wide disturbances to be used for civil defence planning, later supplemented by a fifth case (2018). These cases underline the possibility that electricity supply in times of heightened alert, grey zone activities, or war can be affected with direct as well as indirect means for extended time periods.

3.5 Preparedness & total defence

In Sweden, crisis preparedness and total defence is about strengthening society's ability to prevent and manage crises and war. Preparedness measures are expected from authorities, businesses, municipalities, regions, volunteers, and individuals living in Sweden (MSB, 2023a).

Total defence are the functions and activities required to prepare Sweden for war, consisting of military defence and civil defence.

Crisis preparedness is about the ability to prevent, withstand, and manage crisis situations. The ability is built through education, training, and the organisation and structures created before, during, and after a crisis. All of society is expected to take responsibility for developing the crisis preparedness work (MSB, 2023b).

Civil defence is about all of society's resilience during war or risk of war. It aims to protect the civilian population during war. In times of war or risk of war, the civil defence should be able to support the Swedish Armed Forces. The goal of the civil defence is having ability to (MSB, 2023b):

- protect the civilian population
- maintain CEs
- maintain necessary supply flows (here denoted critical flows)
- contribute to the military defence's capability during armed attack or war
- maintain society's resilience against external pressures and contribute to strengthened will-to-defend
- contribute to strengthening society's ability to prevent and manage severe stresses on society in peace
- contribute to the ability to partake in international peacekeeping and humanitarian efforts.

Civil preparedness is an umbrella term for crisis preparedness and civil defence. The two are to augment each other in joint processes for coordination, planning, and preparation. Civil preparedness should be designed to withstand war. The civil preparedness system aims to manage peacetime crisis situations, risk of war, and war. Ultimately, civil preparedness aims to prepare Sweden for any societal disruption that risks hurting it (MSB, 2023b).

The Swedish Ministry of Defence in a government decision (2020) states that total defence planning should take the following as a starting point: being able to deal with a security crisis involving severe disruptions to the functioning of society, during at least three months. Furthermore, it is presumed that a heightened state of alert is enacted during the three months. Additionally, it is presumed that acts of war take place in Sweden during part of those three months. This timeframe is reiterated in a proposition adopted by the parliament of Sweden (Government Offices of Sweden, 2020).

3.6 Roles & responsibilities in Swedish preparedness

Civil preparedness is fundamentally structured by three principles acting as background for regulations and mandates. They appear in official reports, government propositions, and legislative history, but are not specifically defined in law (MSB, 2018):

- *The principle of responsibility* meaning those responsible for a function in normal situations have corresponding responsibility during societal disruptions. It includes responsibility to act even in uncertain conditions, as well as support and coordination with related actors.
- *The principle of proximity* meaning societal disruptions are to be managed where they occur by those most closely affected and responsible. It entails geographical and organisational proximity.
- *The principle of equality* meaning actors should not make larger changes than is required by the situation. During disruptions the entity is to perform as closely as possible to the performance during normal conditions.

A significant structural reform on the basis of Swedish government official report 'Struktur för ökad motståndskraft' (SOU, 2021:25) has been enacted, partly by the decree on government agencies preparedness (2022:524) and decree on civil area-responsible county administrations (2022:525). The Swedish Ministry of Defence has decreed that CEs be divided into ten civil preparedness sectors (Försvarsdepartementet, 2022). The report (SOU, 2021:25) states the justification for which activities are classified as CEs, and that these have been divided into sectors based on interdependencies and on the CEs considered most central to maintain. The sector system formally organises preparedness-related authorities. There are 60 officially designated preparedness authorities. Many CEs are maintained by other actors than the state – including municipalities, regions, private businesses, public companies, and volunteer organisations. Hence, preparedness authorities are to cooperate with relevant actors related to each sector. The sectors are interdependent, requiring cross-sectoral cooperation. The Swedish Civil Contingencies Agency (MSB) is responsible for taking a holistic approach based on a total defence perspective, supporting the sectors in their efforts (SOU, 2021:25). Each civil preparedness sector is described in E.

Roles and responsibilities are further regulated by numerous laws, decrees, and provisions. Some examples relevant to the context:

- Municipalities have a geographical area-based responsibility before and during extraordinary events in peacetime and heightened state of alert (SFS, 2006:544).
- The municipality has ultimate responsibility to provide necessary support and help to those in the municipality needing it (SFS, 2001:453).
- Rescue services' responsibility is primarily regulated in relation to the municipality (MSB, 2021b; SFS, 2003:778).
- Grid concession holders are to ensure outages do not exceed 24 hours (SFS, 1997:857).
- There are regulations on outages for district heating (SFS, 2008:263; Swedish Energy Agency, 2013).
- For drinking water supply, it is prescribed that relevant actors should decrease risk of severe disruptions (MSB, 2011).
- Operators of electronic communications networks are mandated to ensure reasonable operational reliability (SFS, 2003:389).

For many CIs in Sweden, the ownership, operation, and maintenance have been distributed among several private and public entities, leading to institutional fragmentation. It has been shown that contractual arrangements such as service-level agreements are important in shaping resilience of deregulated CIs. Contracts are used to incentivise actors to certain behaviours and has been shown to maintain high reliability levels (Cedergren, et al., 2018).

In summary, CEs are in different ways required to mitigate disruptions, or plan to manage them. This includes effects of disrupted electricity supply, and thus, CEs must prepare to handle such disruptions. To do so, disruption effects on the CEs must be analysed.

4 Results & analysis

Processed expert elicitation data are presented and analysed. Quantitative and qualitative data for eight CEs are included (see 2.2.3 for overview of CEs).

4.1 Individual CE assessments

Integrated qualitative and quantitative data are presented for each individual CE. All quantitative data in 4.1 includes changes from the interview and post-interview processing as described in 2.2.1 and 2.2.6.

4.1.1 Municipal meal production

The municipal meal production CE maintains the function of municipal meal supply. The function includes sourcing, preparing, and transporting meals for schools, preschools, and special housing within one municipality. It was represented by an expert Meal Strategist. The CE had five production kitchens and around 30 receiving kitchens. Quantitative assessments are presented in Figure 4. An assumption was that auxiliary power for three production kitchens were operational. Unstandardised confidence levels were around 70-90%, dropping as outage length increased.

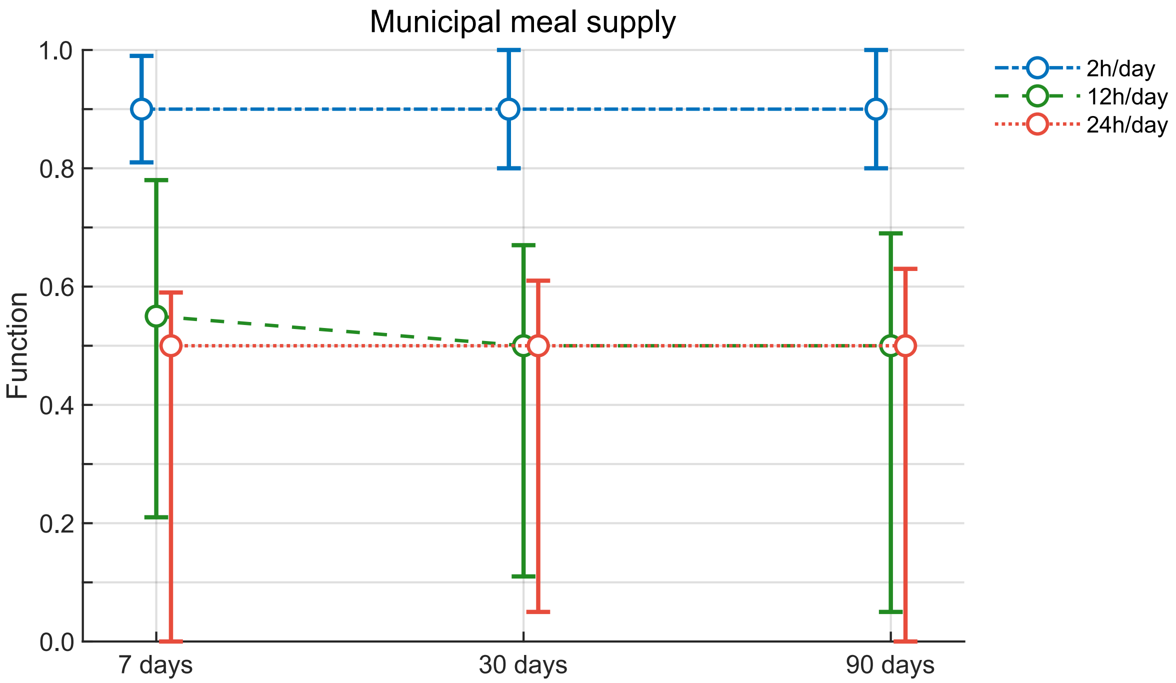

Figure 4. Assessments of function (municipal meal supply) maintained by CE (municipal meal production) during electricity outage scenarios, standardised to 90% confidence levels. Top and bottom horizontal lines mark highest and lowest plausible assessments, circles mark best assessments.

Three trends are immediately identifiable. Firstly, intervals are small for short outages (2 hours/day) and large for medium and long outages (12 hours/day, 24 hours/day) regardless of scenario duration (7 days, 30 days, 90 days). Secondly, best assessments are similar for the same outage lengths regardless of scenario duration. Thirdly, best assessments for medium and long outage lengths are similar, and also significantly lower than for short outages.

The first trend indicates low variability in CE performance for short outages. For medium and long outage length it indicates higher uncertainty. Unstandardised assessments and reasoning given in the interview point towards it being a combination of variability and epistemic uncertainty.

The second trend shows performance is more sensitive to outage length than scenario duration. Best assessments are almost identical for each outage length respectively, meaning there is very small correlation between scenario duration and performance, if any. It suggests that the CE's ability to cope with electricity supply disruptions is not significantly deteriorated in prolonged scenarios.

The third trend indicates some critical threshold between 2 and 12 hours of electricity outage per day. After that threshold additional outage hours seem to have less effect. Based on interview results, there are point-like thresholds within that range (e.g. after a certain time frozen food is spoiled, or it becomes too late to prepare upcoming meals requiring electrical equipment).

Lastly, best assessments are at or above 50% function for all scenarios. This indicates relative robustness against electricity disruptions. The expert said they were used to dealing with some disruptions (e.g. in water) and that 'cold foods are always an option'. Interval sizes indicate that this perceived robustness is coupled with large uncertainty for medium and long outages. Lowest plausible bounds drop as low as 0% for long outages and 5-20% for medium outages. That would imply low levels of robustness.

Takeaways (municipal meal production)

- Uncertainty appears small for short outages and large for medium and long outages, regardless of scenario duration.
- Function maintained correlates strongly negative to outage length, and weakly, if at all, to scenario duration.
- Most function loss occurs before outages exceed 12 hours per day.
- The CE appears to have medium robustness against electricity supply disruptions, but for medium and long outage lengths these assessments are uncertain.

4.1.2 Fiber network operator

The fiber network CE maintains the function of city fiber network (internet, telecommunications) within one municipality. The CE is responsible for operation, construction, and maintenance of switches, fiber cables, and canalisation. It was represented by an expert Security Officer. Quantitative assessments are presented in Figure 5. A stated assumption of the expert was that important end customers have their own battery backup. It was also stated that six hours of electricity outage was considered a critical threshold after which controlled shutdown would have to commence. Unstandardised confidence levels were 90% for short and medium outage lengths, and 100% for long outage lengths.

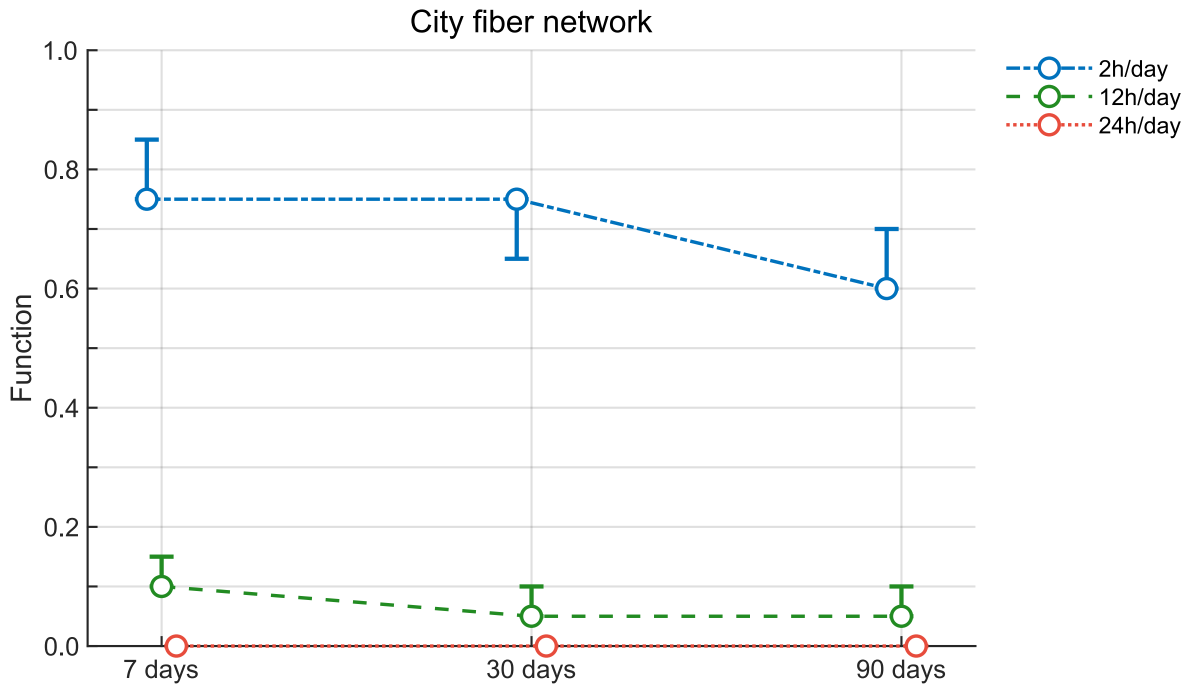

Figure 5. Assessments of function (city fiber network) maintained by CE (fiber network operator) during electricity outage scenarios, standardised to 90% confidence levels. Top and bottom horizontal lines mark highest and lowest plausible assessments, circles mark best assessments.

The interval size trend shows that uncertainty appears small. In addition, there is a clear correlation between longer outage lengths and smaller uncertainty. This has to do with the CE's direct functional dependence on electricity. For technical reasons it is physically impossible to maintain fiber-optic telecommunications and internet connection without electricity. So, it is a necessary dependence (e.g. compared to meal production where some foods can be prepared without electrical equipment). The interview clarified that after six hours outage, air conditioning cannot be maintained and controlled shutdown must commence. For short outage lengths, area switches without UPS systems would instantly go out of operation.

The best assessment trend reveals that function correlates strongly negative to outage length rather than scenario duration. It implies that the CE is not sensitive to scenario duration. Still, there is a slight negative trend as duration increases. This ties into a third trend, that function for medium and long outage lengths are very low, and for short outage lengths significantly higher. It implies the CE is very vulnerable to increasing outage lengths, where 24-hour a day outage guarantees complete function loss. Again it can be attributed to the necessary dependence on electricity. It can then be inferred that the CE is not robust against disruptions, although insensitive to whether duration is prolonged.

Takeaways (fiber network operator)

- Uncertainties are small and correlate strongly negative to outage length because the system is necessarily dependent on electricity, thus technical ramifications reduce possible outcomes.
- Best assessments correlate strongly negative to outage length, where 6 hours is a critical threshold after which controlled shutdown must commence.
- The CE is very vulnerable to electricity supply disruptions – where 24-hours a day outage guarantees complete function loss – but is relatively insensitive to whether scenario duration is prolonged.

4.1.3 Municipal rescue services

The rescue services CE maintains the function of municipal rescue services within one specific municipality. It includes responding to emergencies, and preventive work like fire safety inspections. It was represented by an expert Operations Chief. Quantitative assessments are presented in Figure 6. The expert stressed that assessments were done based on the outage scenario condition that all other organisations and functions in society worked normally. Unstandardised confidence levels were 100% except for 12- and 24-hour 90-day scenarios, where it dropped to 70-80%.

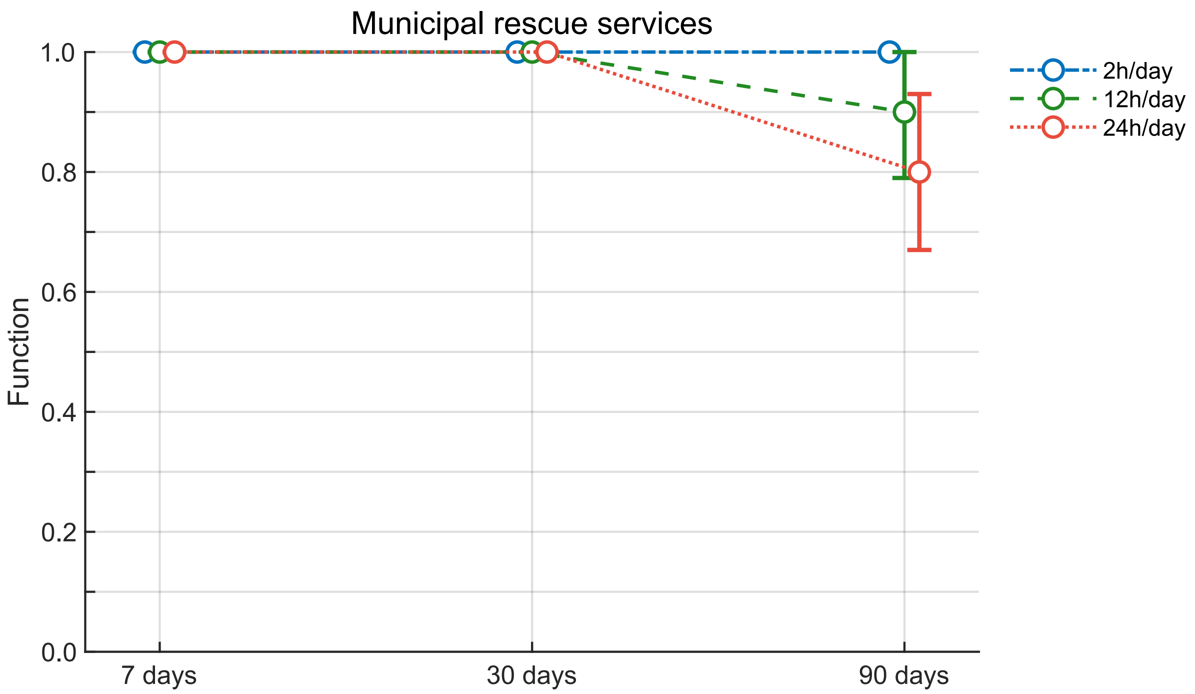

Figure 6. Assessments of function (municipal rescue services) maintained by CE (rescue services) during electricity outage scenarios, standardised to 90% confidence level. Top and bottom horizontal lines mark highest and lowest plausible assessments, circles mark best assessments.

Two patterns emerge. One, for most scenarios, function is at 100% with complete certainty. Two, the only exceptions to this are medium and long outages with 90-day scenario durations where function is somewhat diminished. The results indicate high robustness against electricity disruptions. The interview showed that electricity was needed to some extent, e.g. using industrial-grade washers, operating communication systems, and heating the building during winter. However, it also revealed that the CE has significant ability to supply the electricity it requires, e.g. UPS systems, diesel auxiliary power, and fuel supply. That explains how robustness can be high. It is further explained by adaptability of operational methods (e.g. alternative solutions to electronic communications).

Interval size is not negligible for 90-day medium and long outages. Judging by the interview it is due to both variability (e.g. as auxiliary power starts breaking down) and epistemic uncertainty (e.g. unknown if diesel supply will be sufficient). For longer scenarios the CE was dependent on external fuel supply, relying mainly on the municipality crisis management. It could also relate to adaptation of methods (e.g. if equipment is washed by hand instead of industrial grade washers, contamination levels could over time build up to debilitating levels). The CE is resilient although some function loss appears for 90-day scenarios. It is clear that this type of CE differs from many others, i.e. it is designed for crisis response rather than being on the receiving end of a crisis.

Takeaways (municipal rescue services)

- Functions levels are at 100%, with two exceptions where function slightly decreases: 90-day scenarios with 12h/day and 24h/day outages.
- Perceived uncertainty is zero except in the two mentioned scenarios, explained by limited dependency on electricity, and very robust internal solutions (e.g. UPS, auxiliary power, alternative work methods).
- The CE is resilient against all examined electricity supply disruptions, although slightly more sensitive to 90-day disruptions.

4.1.4 Municipal management

Two separate municipal management CEs were examined, allowing some comparison. They maintain the specific function of municipal crisis management in their respective municipality. The function includes e.g. coordination, planning, communications, prioritisation of resources, and execution of BCM plans, during some situation where municipal crisis management is required. Such a situation could be anything from accidents or flooding to electricity disruptions or fires. They are numbered (1) and (2) to separate results. The CEs were represented by a Preparedness and Safety Coordinator (1) and a Crisis Preparedness Coordinator (2). Quantitative results for (1) are presented in Figure 7, and for (2) presented in Figure 8. The expert for (1) stated the assumptions that their auxiliary power units were functional, and that fuel supply would be somewhat challenging at later stages in a long duration scenario. The CE had relatively recent experience of a longer outage. The expert for (2) stated the assumption that as time passes there will be a new state of normalcy in which negative effects from the same outage lengths will be smaller than at earlier stages of the scenario. Expert (2) assumed auxiliary power was not fully available. Expert (2) also clarified that 90-day scenarios were hard to imagine, thereby indicating high uncertainty in those assessments. It does not necessarily mean that assessed confidence levels given the predefined scenario conditions must be small, but could simply suggest uncertainty in those conditions. Unstandardised confidence levels for (1) were mostly around 80-100%, dropping as outage length increased. For (2) they were in the 50-80% range, also dropping with outage length.

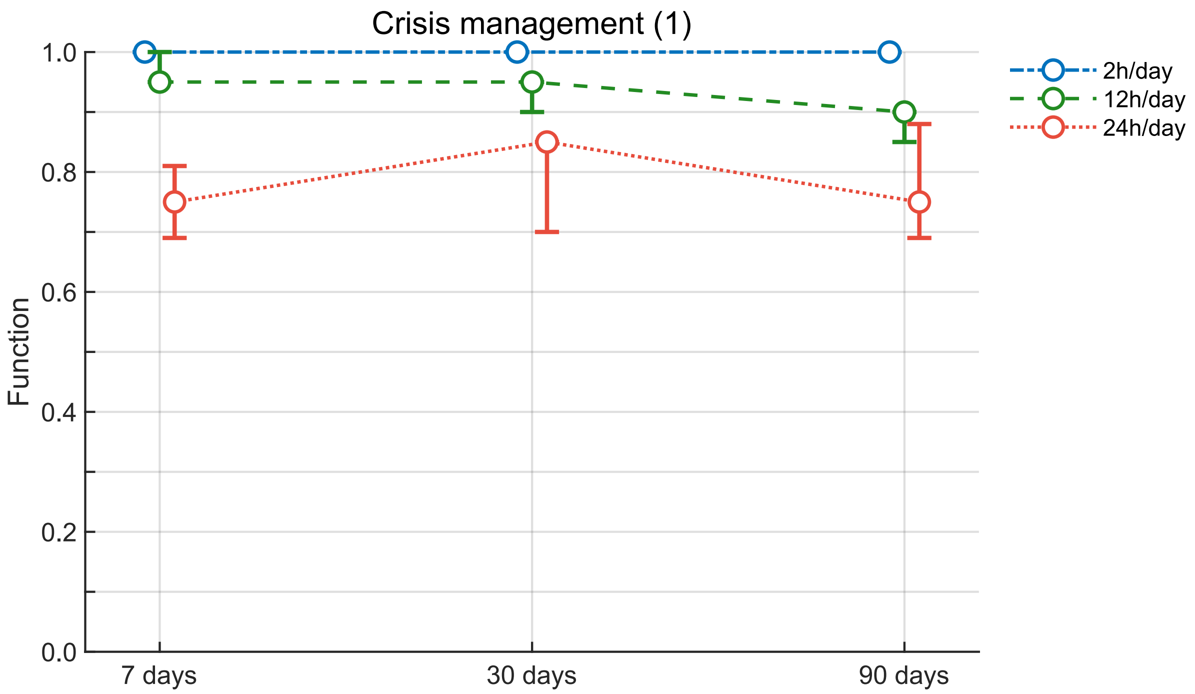

Figure 7. Assessment of function (municipal crisis management (1)) maintained by CE (municipal management (1)) during electricity outage scenarios, standardised to 90% confidence level. Top and bottom horizontal lines mark highest and lowest plausible assessments, circles mark best assessments.

Several trends can be seen for (1). Function is relatively high for all assessed scenarios. The worst 'best assessment' is 75%, applying for long outages in 7-day and 90-day durations. This indicates a high robustness against disruptions in general, including prolonged scenarios.

Furthermore, function decreases as outage length increases. There is not such a clear correlation between scenario duration and function. This implies that the CE is more vulnerable to long outage lengths, and less vulnerable to whether such outage lengths occur repeatedly during a prolonged scenario.

The interview indicated that this relates to communication systems used in crisis management. It might hamper the communication needed to timely execute coordination. Some systems (e.g. computers, information-sharing systems, internet connection) are needed for full function with regards to planning and information (e.g. from the regional level) used for decision-making. Based on the trends such effects seem to arise on an outage length basis unaffected by scenario duration, possibly because coordination is near real-time and information becomes obsolete as time passes.

Lastly, interval sizes are very small, increasing with outage length. As indicated by the interview, that is due to both the expert not knowing how well adaptive measures or procedures will work, and variability like possible breakdown of auxiliary power. The lowest part of any interval sits at around 70%, suggesting high robustness.

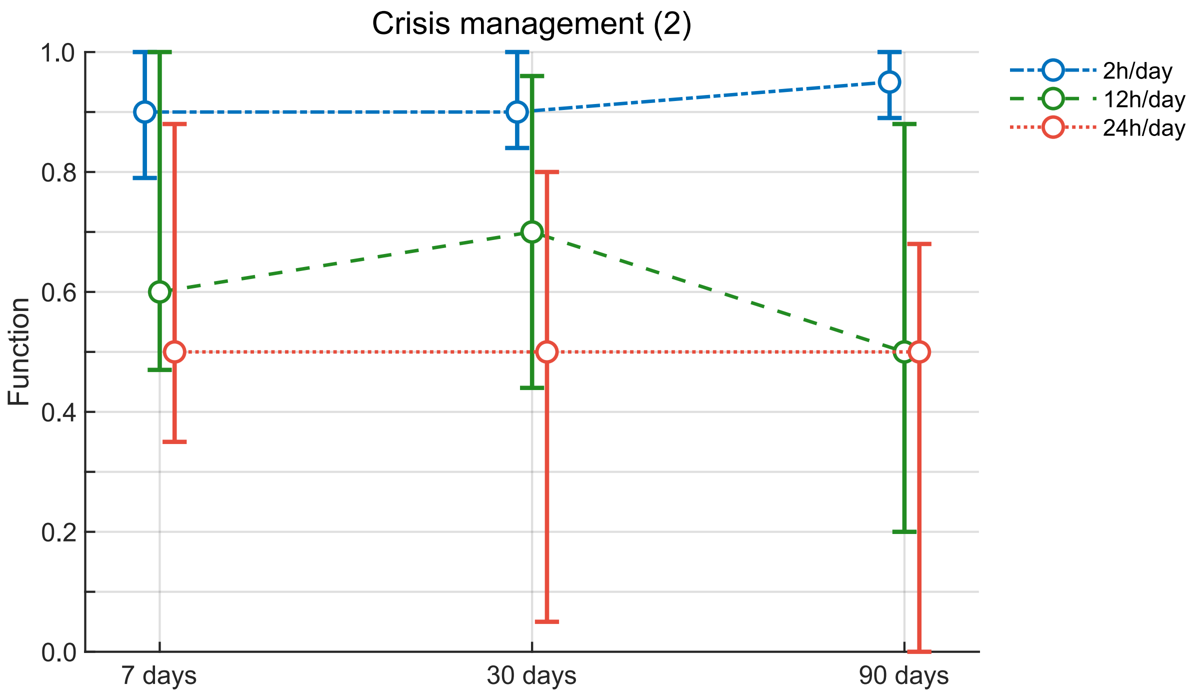

Figure 8. Assessment of function (municipal crisis management (2)) maintained by CE (municipal management (2)) during electricity outage scenarios, standardised to 90% confidence level. Top and bottom horizontal lines mark highest and lowest plausible assessments, circles mark best assessments.

For (2) there are both similarities and differences compared to (1). For (2) function clearly correlates negatively to outage length, as for (1). Conversely, there is significant difference in 'best assessment' levels. For (2) the worst 'best assessments' are at 50%, and medium outage length assessments are considerably lower than for (1). That exemplifies how robustness could vary between different CEs maintaining the same type of function. However, it might be caused by varied assumptions. In contrast to (1), (2) assumed auxiliary power was not fully available. It was not fully clarified in the interviews whether this was due to internal abilities or varied assumptions about external conditions.

Another similar trend is that interval size increases with outage length. But for (2) the interval sizes in all scenarios are much larger than for (1). It is likely not due to substantial dependency on electrical systems, as the interview showed that alternatives exist (e.g. physical messengers, pre-determined meet-up times and locations, proactive planning). It is likely that some of it is due to epistemological uncertainty. For example, (2) explained that time of day was an uncertainty (i.e. whether outage occurs when they have lots of work). Interval sizes seem not to correlate with scenario duration.

Takeaways (municipal management)

- Function levels for (1) are high in all scenarios whereas for (2) they drop to medium levels for longer outage lengths, indicating medium to high robustness.
- Function levels highlight how disruptions might have varied consequences for a given CE type, but could also be due to varied expert assumptions.
- Outage length correlates with uncertainty, being generally small for (1) and significantly larger for (2), again highlighting how disruption effects might vary for a given CE type.
- The CE type seems insensitive to scenario duration, possibly because it relies on real-time coordination based on constantly changing information, thus losing function during specific outage hours regardless if they occur 7 or 90 days in a row.

4.1.5 Wastewater utilities

The wastewater utilities CE maintains the function of wastewater management for two municipalities. The examined function includes transporting wastewater from connected users, processing it, and producing biogas. It also includes releasing processed wastewater into waterways, lakes, or the sea. The organisation included one major treatment plant, several smaller plants, water towers, piping, and around 150 pumping stations. It was represented by an expert Security Officer. Quantitative assessments are presented in Figure 9. A stated assumption was that no auxiliary power was available. In the interview it was clarified that the organisation did not have solutions for auxiliary power. It was also stated that the CE had electricity supply from three separate local distribution grids. Unstandardised confidence levels ranged from 60-100%, generally being higher for long outage lengths.

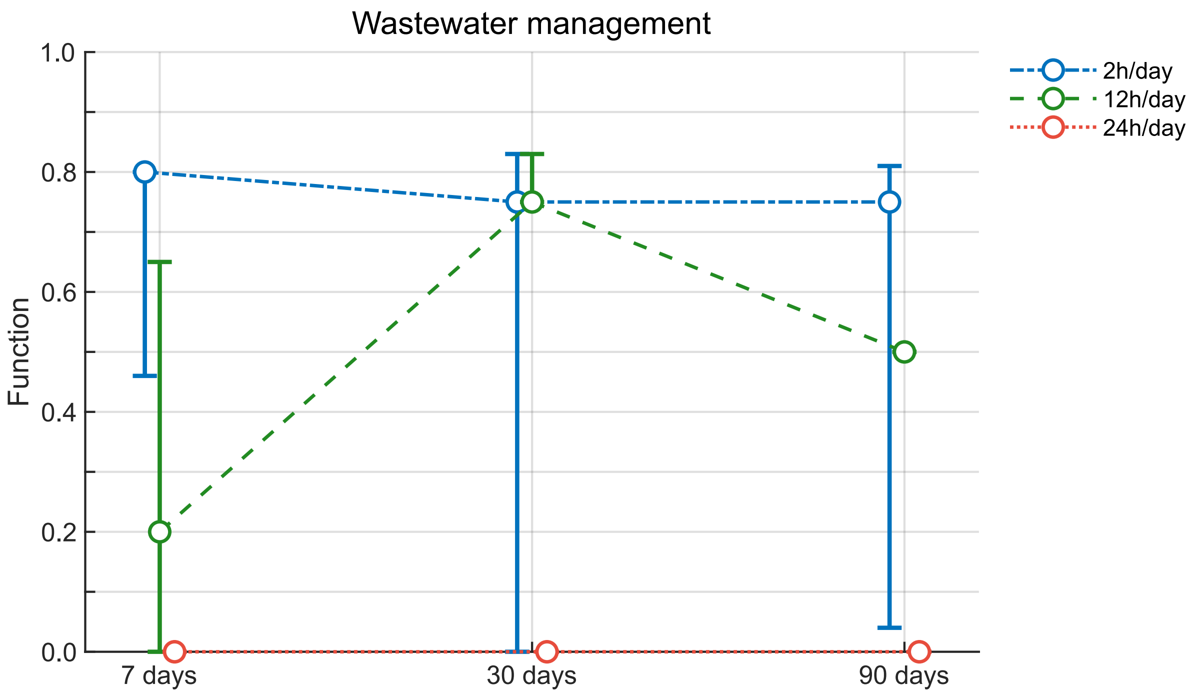

Figure 9. Assessment of function (wastewater management) maintained by CE (wastewater utilities) during electricity outage scenarios, standardised to 90% confidence level. Top and bottom horizontal lines mark highest and lowest plausible assessments, circles mark best assessments.

It appears that long outage lengths with certainty lead to complete loss of function, regardless of scenario duration. For medium and long outage lengths, best assessments range from 20% to 80%, indicating some robustness.

A clear interval size trend is not discernible. For medium outage length, interval size is large for 7-day duration and very small for 30-day and 90-day durations. In addition, best assessments for the 30- and 90-day durations are higher than for 7 days. This indicates higher initial vulnerability to medium outage lengths. It might be due to extra function loss while adjusting, but it cannot be determined with certainty from survey or interview answers. It was described that resources will be prioritised to the drinking water supply organisation within the same CE, in case of disruptions. This helps explain interval sizes, as there is uncertainty regarding how drinking water is affected and thus which resources are available.

The interval size trend for short outage lengths is almost the opposite. It is not clear why. It might be because system design favours consistency, like the explanation for the drinking water CE (see 4.1.6). It could also be due to epistemological uncertainty, although it is counterintuitive that such uncertainty would place the lowest bound much lower for 2-hour outage lengths than for 12-hour lengths.

Takeaways (wastewater management)

- 24-hour a day outage guarantees complete function loss regardless of scenario duration.
- For medium outage lengths, interval sizes are large for the 7-day duration and very small for 30- and 90-day durations, indicating high uncertainty during an initial adjustment phase.
- For short outage lengths it is the opposite – intervals increase with scenario duration – possibly because system design favours consistency with either primary or reserve operations.

4.1.6 Drinking water utilities

The drinking water utilities CE maintains the specific function of drinking water supply. It includes production and distribution of drinking water for a conglomerate of municipalities including a large city. Its systems entailed water treatment plants, piping, pumping stations, and the like. The CE also had suborganisations maintaining the functions of wastewater management, rainwater management, and waste disposal, but only the function of drinking water supply was examined. The CE had fixed and mobile auxiliary power solutions. It was represented by an expert Plant Engineer. Quantitative results for are presented in Figure 10. It was stated that boiling requirements could be used if quality parameters were not met. It was also stated that normally 80% of the drinking water was delivered into their systems in correct quality and pressure by external actors. It was assumed that those external actors operated at normal function, and that diesel supply for auxiliary power was not a limiting factor. Unstandardised confidence levels ranged from 50-90%, generally decreasing with scenario duration.

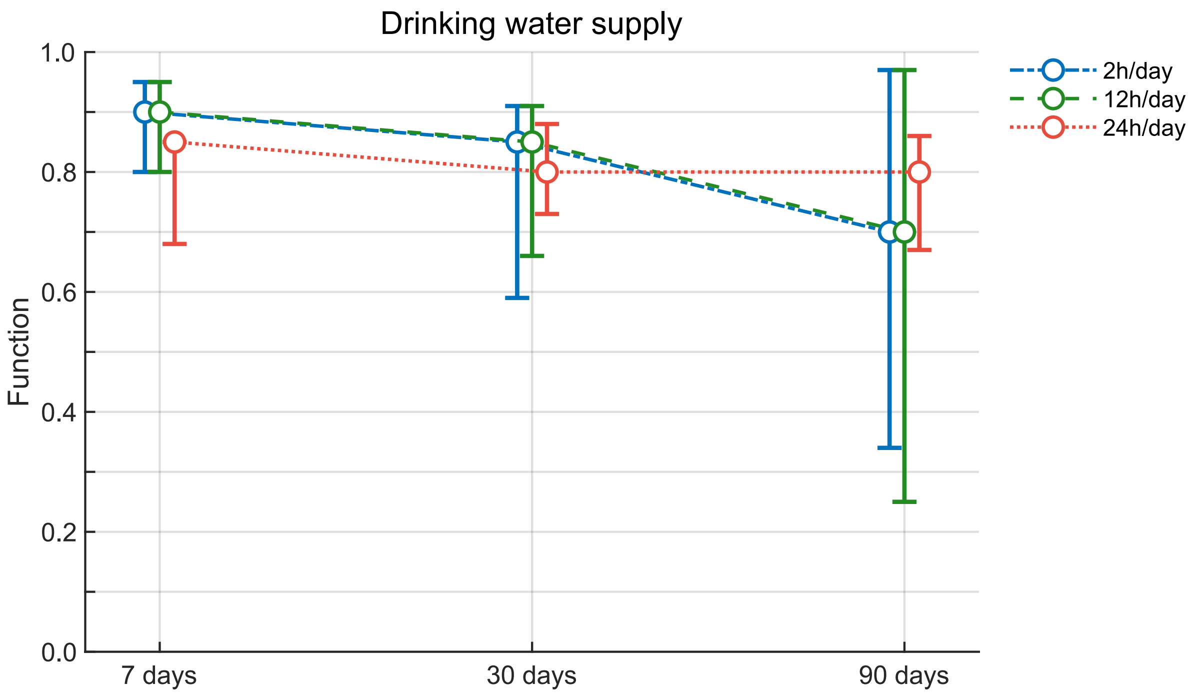

Figure 10. Assessment of function (drinking water supply) maintained by CE (drinking water utilities) during electricity outage scenarios, standardised to 90% confidence level. Top and bottom horizontal lines mark highest and lowest plausible assessments, circles mark best assessments.

A general trend is that interval size correlates with scenario duration. That implies uncertainty regarding effects of prolonged disruptions. Interval size also seems to correlate negative to outage length. It is best explained by a clarification from the interview, that smooth operation with electricity from either the grid or auxiliary power enabled a higher and uniform quality level (i.e. frequent shifting between grid and auxiliary power decreased quality). The clarification also points to variability rather than epistemological uncertainty.

All best assessments fall between 70-90%, indicating high robustness. Considering that around 80% of normally maintained drinking water supply was assumed to be delivered by external actors complicates that judgment, though. The CE function consisted in production and distribution, where only 20% of normally maintained water supply was produced within the CE. So, 80% of the delivered end product would be limited only by the CE's distribution capabilities, and not its production capabilities. In a sense, then, the CE's robustness is dependent on the robustness of external entities. Such a distributed manner of supply can itself be a way to achieve redundancy, but one must consider these specific conditions if trying to draw conclusions about drinking water CEs in general based on this data. Geographically widespread outages could also affect the external entities.

Best assessments for 90-day duration show better function for long outage lengths than medium or short. This is also explained by the clarification that not shifting between grid and auxiliary power alternatives promoted drinking water quality, and thus function maintained.

Takeaways (drinking water supply)

- Uncertainty grows with scenario duration, indicating sensitivity to prolonged disruptions.
- Variability decreases with outage length because smooth operation with either grid or auxiliary power promoted high and uniform quality, in contrast to frequent shifting between the alternatives.
- The CE appears robust against electricity supply disruptions but is dependent on external actors providing 80% of the water.

4.1.7 Electricity distribution operator

The electricity distribution CE maintains the function of a local distribution grid. It included distribution of electricity supplied via the regional grid, within one municipality including a city. Scenarios were interpreted as outages occurring at the regional or higher level. The expert was an Electrical Installations Manager. The expert explained that function maintained in the local grid must not be a mirror-image of presupposed outage scenarios. For example, as electricity from the regional grid returns, overload in the local grid could trigger safety fuses taking hours to restore. They used diesel auxiliary power, e.g. for maintaining system surveillance during outages. Unstandardised quantitative results are shown in Figure 11. All assessments lack interval size (i.e. lowest, best, highest are the same) and confidence level is low (20-30%, see D). Without interval size, linear extrapolation does not change any value regardless of confidence level standardised to. This was considered poorly representative of reality, especially because assessed confidence levels were low. The idea that a higher confidence assessment might allow a wider interval was suggested during the interview, but the expert chose not to make changes. Hence, it was decided not to standardise. This speaks to the difficulty in eliciting statistically contingent assessments without empirical data. It could possibly be addressed by adjusted elicitation processes but would then entail trade-offs with other aspects.

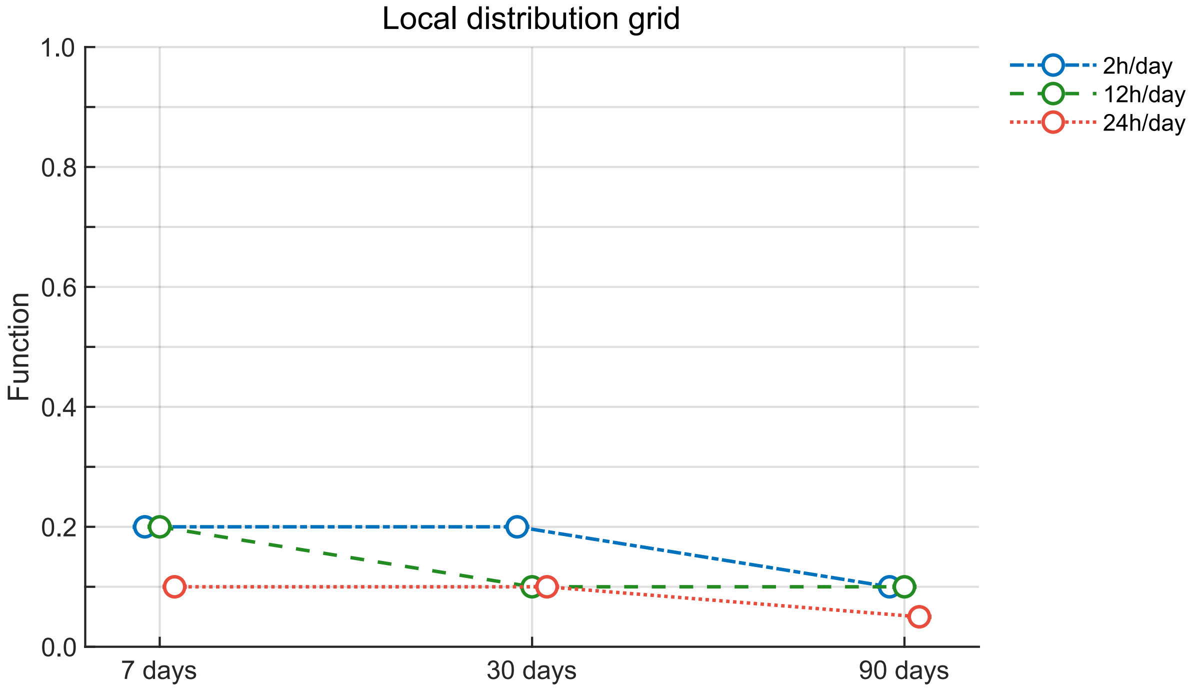

Figure 11. Unstandardised assessment of function (local distribution grid) maintained by CE (electricity distribution operator) during electricity outage scenarios (see D for confidence levels).

All assessments are low, showing the CE is vulnerable to outages of any kind examined. It seems reasonable as CE function is directly interlinked with supply of electricity from the regional grid. There is a negative trend as outage length increases, although function is at 20% already for 2-hour outages. There is a slight negative trend as duration increases, but it appears negligible. Again it seems reasonable, given the direct dependency between electricity supply and CE function.

Interval sizes are non-existent, although confidence levels are low (20-30%). It was not determined exactly what caused this. Three connection points to the regional grid existed, and interview answers showed that during loss of such a connection point complete outage would occur for end users fed through that part of the grid. Such losses indicate function change is not continuous but bound by distinct thresholds, which could help explain why intervals were avoided. Simultaneously, low confidence levels mean that single point estimates leave much to the imagination. This was corroborated as the expert explained it was very difficult predicting the outcome with any certainty. So, it might be concluded that assessments are stapled with significant epistemic uncertainty. But there were also indications of possible variability, e.g. loads were usually higher during winter, increasing risk of triggering fuses as regional electricity supply is resumed.

Takeaways (local distribution grid)

- Epistemic uncertainty is significant.
- The CE is very vulnerable to disruptions due to the direct dependency between function (i.e. local electricity distribution) and regional electricity supply.
- Function is low for all scenarios, and prolonged duration has limited additional impact.

4.2 Comparison of CEs

In this chapter, results from different CEs are analysed and visualised in relation to each other.

4.2.1 Outage scenario comparison

To allow better comparison, an overview of quantitative results for all examined CEs is presented in Figure 12. An apparent disorganisation accentuates how varied assessments can be for different CEs, highlighting a need for CE-specific analyses to guide mitigation and recovery related decisions. It is clearly discernible that most CEs are rather insensitive to prolonged scenario duration (i.e. 7, 30 or 90 days), at least compared to how vulnerable they are to increased outage lengths (i.e. 2, 12 or 24 hours per day). Function does generally drop for longer durations, but hardly at a spectacular rate. Length of individual outages seem a much stronger driver for function loss. Hence, efforts to minimise individual outage lengths for CEs (e.g. Styrel) should be premiered. Nonetheless it bears repeating that these assessments isolate first-order effects. So, it is possible that covering higher-order effects from dependencies on other entities affected by the electricity disruptions might yield more significant impact trends for scenario duration.

Some degree of categorisation could be informed by the comparative results. For example, the two best performing CEs (the municipal rescue services and municipal organisation for crisis management) are by nature designed for responding to crises and disruptions. Contrarily, the worst performing CEs (the fiber network operator and electricity distribution operator) maintain functions that are necessarily dependent on electricity due to technical reasons.

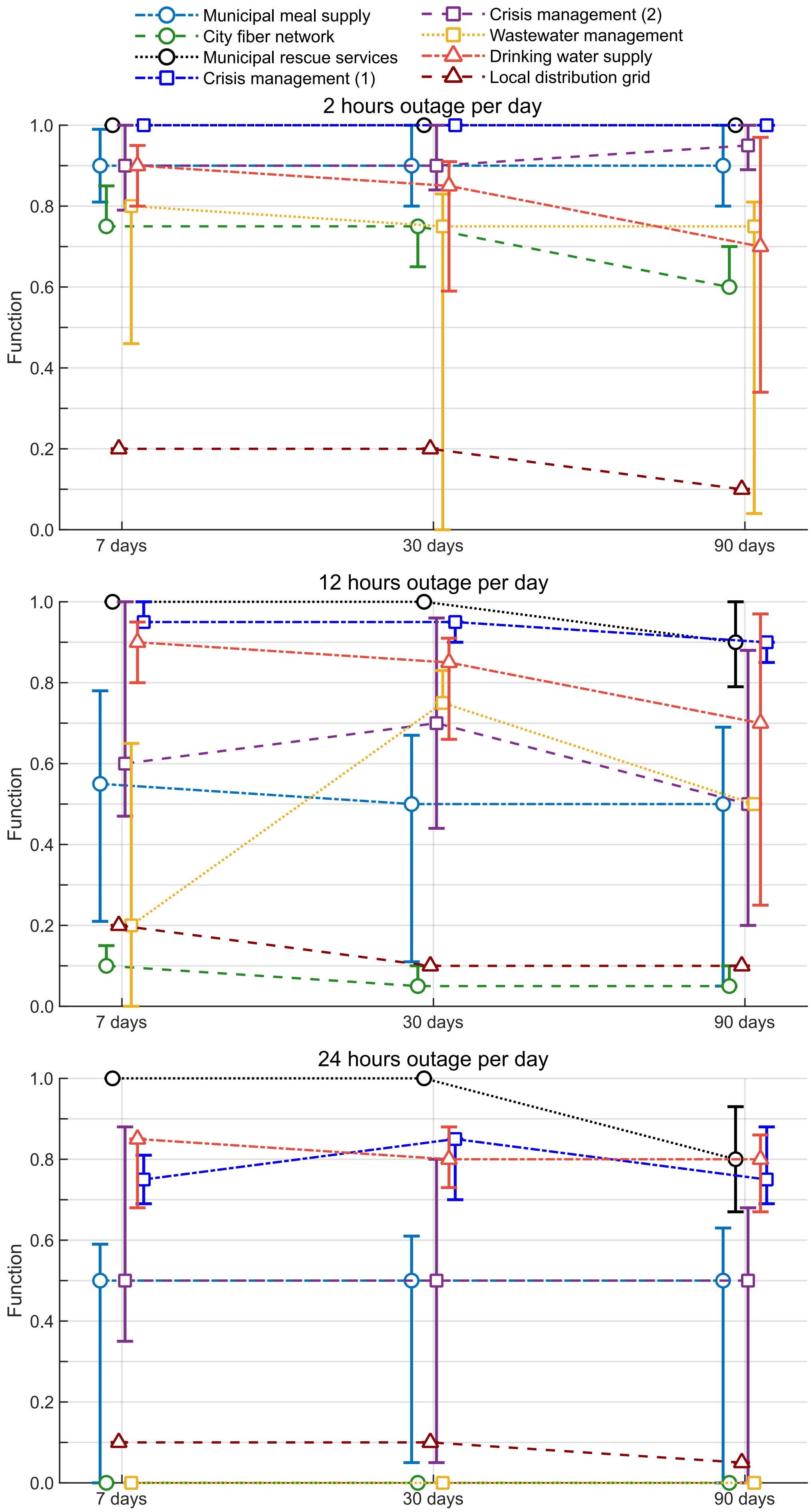
Municipal meal supply
City fiber network
Municipal rescue services
Crisis management (1)
Crisis management (2)
Wastewater management
Drinking water supply
Local distribution grid
2 hours outage per day
12 hours outage per day
24 hours outage per day
Function
1.0
0.8
0.6
0.4
0.2
0.0
7 days
30 days
90 days

Figure 12. Assessment of function maintained by eight different CEs during electricity outage scenarios, standardised to 90% confidence level (local distribution grid is unstandardised). Top and bottom horizontal lines mark highest and lowest plausible assessments, symbols mark best assessments. Legend denotes the specific functions assessed.

Takeaways (outage scenario comparison)

- CEs are relatively insensitive to prolonged duration (consecutive days with outages) and more vulnerable to increasing outage length (hours/day), highlighting a need to prioritise efforts to minimise individual outage lengths (e.g. Styrel).
- Assessments vary greatly between different CEs, showing the importance of CE-specific analyses to guide mitigation and recovery related efforts.
- Accounting for cascading effects might yield more considerable impact trends from increased duration.

4.2.2 Planned outages

Table 2 shows assessed change in function maintained if outages are planned (advance information regarding outages available to CE) instead of unplanned (no advance information available, as for results in 4.1).

Table 2. CE function maintained in the 9 scenarios if outages were planned instead of unplanned.

Change in function maintained if outages are planned instead of unplanned									
CE	**2h 7d**	**12h 7d**	**24h 7d**	**2h 30d**	**12h 30d**	**24h 30d**	**2h 90d**	**12h 90d**	**24h 90d**
Municipal meal production	Better	Better	Better	Better	Better	Better	Better	Better	Better
Fiber network operator	Better	Same	Same	Same	Same	Same	Same	Same	Same
Rescue services	Same	Same	Same	Same	Same	Same	Same	Better	Better
Municipal management (1)	Same	Same	Same	Same	Same	Same	Same	Same	Better
Municipal management (2)	Better	Better	Better	Better	Better	Better	Better	Better	Better
Wastewater	Better	Better	Same	Better	Better	Same	Better	Better	Same

utilities									
Drinking water utilities	Better	Better	Better	Better	Better	Better	Better	Better	Better
Electricity distr. operator	Better	Better	Same	Better	Same	Same	Same	Same	Same

Planned outages were assessed to improve function compared to unplanned in 40 of 72 cases, and in the rest function was unchanged. One observable trend is that 'same'-assessments coincide with scenarios where best assessments were close to 0% or 100%. That is uncontroversial, since near-complete function loss seems only to occur for CEs substantially dependent on electricity. For these scenarios and CEs it is reasonable to assume no auxiliary power is available. Then it is logical that advance information of outages will not improve function. Conversely, if 100% function is maintained during unplanned outages, it is reasonable to assume advance information could not further improve performance.

Several experts mentioned that advance information could allow better planning, and as a result higher function. Depending on the CE it could be possible to execute mitigating measures before the outage, e.g. filling up water towers, preparing food in advance, or installing mobile auxiliary power at critical nodes. Higher function means less disruption to critical flows and thus reduced societal impacts.

Takeaways (planned outages)

- If outages are planned instead of unplanned, function maintained improves for most CE/scenario combinations and is unchanged for the rest, showing CEs generally are less affected if outages are planned.
- For CEs and scenarios in which planned outages did not improve assessed function compared to unplanned outages, assessments were close to 0% or 100%.
- This emphasises the value of communicating potential outages as early as possible to minimise societal consequences.

4.2.3 Contextual cases

The contextual cases (see A) were used to elicit assessments of how wider contextual factors could impact CEs. Table 3 shows change in function maintained if contextual factors were added to basic outage scenarios where peace-time conditions were assumed (i.e. change compared to assessed function level without contextual factors, as presented in 4.1).

Table 3. Effects of contextual factors on function maintained during outage scenarios, compared to outage scenarios without contextual factors.

Change in function maintained if outages occur during contextual cases			
CE	**Grey zone**	**Heightened state of alert**	**War**
Municipal meal production	Worse	Worse	Worse
Fiber network operator	Same	Same	Worse
Rescue services	Worse	Worse	Worse
Municipal management (1)	Worse	Worse	Worse
Municipal management (2)	Same	Same	Worse
Wastewater utilities	Same	Same	Worse
Drinking water utilities	Worse	Worse	Worse
Electricity distribution operator	Same	Same	Worse

4.2.3.1 Grey zone

Some CEs can maintain the same function in the grey zone case. However, it might still strain them in certain ways, e.g. increased work burden for personnel or need for guarding facilities. The fiber network CE is normally subject to daily cyberattack attempts which it successfully deals with, and the expert believed that personnel would rally in times of societal disruption, thus counteracting potential function loss from personnel shortage. The fiber network expert stated:

> […] the grey zone threat isn't as severe as discussions in society and media conclude. Our organisation can deal with these types of attacks for prolonged periods of time. […] for the function of our city fiber network we assess that it will not be affected. […] if anything, it would be fear and worry in society that could affect our employees.

Most CEs still described a risk of personnel issues leading to lower function maintained. If personnel are overworked, unable to reach the workplace due to disruptions, or unwilling due to fear, function can be affected. Additionally, all experts saw some risk related to pressure or extortion measures against key individuals. For example, sensitive information about the CE could be leaked and used for sabotage. The rescue services expert noted that increasing numbers of accidents and disrupted water supply could impact their function significantly. Seven out of eight CEs rely on diesel-fuelled auxiliary power units, pointing to insufficient diesel supply as a potential risk. Experts highlighted the importance of mentally prepared personnel, unifying and skilled leadership, proactively created BCM plans, and means of communication internally and with the public. The wastewater utilities expert highlighted that resources to guard facilities is key to avoid function loss.

4.2.3.2 Heightened state of alert

As for grey zone, some CE functions are unchanged by the heightened state of alert. Several experts said their CE would be additionally strained, although unclear to what extent. The specific contextual case focuses on the mobilisation phase and plays out in a shorter duration (days up to a few weeks), increasing probability that CE diesel stockpiles for auxiliary power will last. It does not mean that stockpiles last longer during heightened alert in general, which could remain in place for extended time periods. All experts acknowledged possible issues relating to deployment duty, e.g. personnel leaving the CE to serve in the Armed Forces. The drinking water expert stated:

> We might lose personnel to deployment duties [...] there are small margins in staffing [...] someone gets called up for duty, someone calls in sick, and operations ‘collapse’. Internal readiness measures further increase pressure on staff. We have been nagging [...] for assigning personnel deployment duties within the organisation. It has not been done yet but will be.

Conversely, some experts believed the heightened alert might increase their freedom of action, because personnel held deployment duties within the CE and thus could work unrestricted by peacetime conditions, e.g. time-of-day regulations or vacations. Several experts concluded that adequate deployment duties for personnel, and proactive coordination with the armed forces (e.g. so CE vehicles are not requisitioned), are important to minimise function loss.

4.2.3.3 War

During war, assessed function is worsened for all CEs. Several experts said function might be significantly disrupted, especially in the initial phase before adaptation measures and a ‘new normal’ fall into place. However, some experts also mentioned a risk of gradual degradation, e.g. as stockpiles run out, spare parts become unavailable, or personnel resources are exhausted. Most experts explicitly stated that personnel would try their best, adapt to available resources, and not give up. Some experts, mostly from CEs depending on physical infrastructure, suggested that repair work might take long periods of time (e.g. concrete hardening) and require scarcely available resources (e.g. spare parts, trained technicians and electricians). Again, most experts noted the importance of adequate deployment duty assignments for personnel. Some experts pointed to risks with geographically concentrated resources (e.g. all equipment and fuel stockpiles in the same fire station). If such concentrations were subject to kinetic attack, it could greatly degrade CE capabilities. Conversely, if resources are geographically distributed it might be harder to protect them against sabotage or theft. The municipal meal production expert exemplified interdependencies and uncertainty:

> There are so many things to consider [...] e.g. municipal prioritisation of available food and diesel, transportation of food [...] but also that external persons might rally to help, or that some of those we serve leave, and thus that less function is required. [...] are parents of small children assigned deployment duties? Will we have to produce more meals for children whose parents are away?

Most experts mentioned that insufficient diesel supply for auxiliary power would negatively affect function. Several experts raised the idea of regional or national stockpiles (e.g. diesel, extra fire trucks) because individual actors or municipalities do not have the resources to keep stockpiles for more than a few days or weeks. From a societal perspective it might allow improved resource prioritisation, avoiding large stockpiles sitting unused at unaffected CEs while others need the stockpiled resource. It should be noted that some measure of national-level oil stockpiling already is required by law (SFS, 2012:806).

Takeaways (contextual factors)

Grey zone

- Function maintained is worse or at risk of worsening for all CEs.
- CE resilience and societal adaptability might be underestimated.
- Staffing, protecting physical assets, and diesel supply are critical.

Heightened state of alert

- CE functions are worse or at higher risk of worsening.
- Key personnel assigned deployment duties outside the CE is a significant risk.
- Because the case focuses on a shorter mobilisation phase, supply issues are manageable – for longer durations it could be different.

War

- Function maintained is worsened for all CEs.
- Key personnel assigned deployment duties outside the CE is a significant risk.
- Repair work presents a significant bottleneck (e.g. time of repairs, available technicians, spare parts supply).
- Protecting physical assets is critical.
- Supply of resources (e.g. diesel, extra fire trucks, food, spare parts) is a considerable vulnerability, suggesting need for well-coordinated regional stockpiles, or other solutions.

4.2.4 Improvement measures

Based on the interviews, this section presents general improvement measures followed by context-specific measures.

4.2.4.1 General measures

Table 4 presents the most important general improvement measures given by experts. ‘Internal measures’ entail measures that experts deemed possible to implement with the CE’s existing resources or budget. They also include measures that had already been successfully implemented. ‘External measures’ include those that mainly fall under some other organisation’s responsibility, or at least outside the CE’s legal or economic reach. Joint coordination, often including private-public cooperation, seems to be lacking. It should be noted that this is also emphasised by relevant authorities, see e.g. reports ‘Civilt försvar mot 2030’ (MSB, 2022b) and ‘Struktur för ökad motståndskraft’ (SOU, 2021:25).

Table 4. General improvement measures.

Improvement measures to better cope with prolonged electricity supply disruptions				
CE	**Critical types of measures**	**Internal measures**	**External measures**	**Cooperation and coordination**
Municipal meal production	Exercises Coordination	Training and exercises Testing auxiliary power units Isolation boxes for food Stock of disposable tableware	Transport solutions	Access to diesel via municipality preparedness systems Partnerships with local stores and farms Recurring sync of BCM plans within municipality
Fiber network operator	Spare parts access Prioritisation of end users	Auxiliary power units for nodes with only UPS Mobile auxiliary power units Deployment duty for personnel		Svenska kraftnät Regional grid operator Bordering city fiber networks
Rescue	Spare parts	Preparedness plan to	Long-term diesel	Supplier agreements

services	supply Alternatives to diesel power units	limit electricity use Solar panels	supply from municipality	via municipality, e.g. for diesel supply
Municipal management (1)	Fuel storage capacity	Improve plans More exercises, especially with external actors Alternative solutions for communication	Functional telecommunications Clarity regarding telecommunications system function and responsibilities	Private actors within municipality (farmers, local businesses) Other municipalities Electricity grid operators outside municipality
Municipal management (2)	Available auxiliary power Physical communication channels	Command post auxiliary power supply Routines for rendezvous of crisis management team Planning 'Safety points' for informing public Physical messengers	Improved auxiliary power for telecommunications Regional fuel storage	Maintaining chains of communication (muncipality-county-armed forces/national level) Styrel prioritisation lists synced with local and regional grid operators
Wastewater utilities	Auxiliary power units Delay measures (storage) BCM plans	No measures possible with existing resources	Authorisation by owners to tariff users for CE service, in order to finance measures Financing for auxiliary power units	Cooperation and training with owner municipalities Joint diesel stock for municipalities
Drinking water utilities	Increase number of trained personnel More diesel	More training and exercises Digital monitoring systems	Long-term diesel supply plan at societal/municipal level Vehicles for diesel transport	Joint electricity preparedness for entire organisation (including other functions) Framework contract with auxiliary power maintenance actor
Electricity distribution		Auxiliary power for system surveillance	Energy storage facilities (e.g. battery) within	Cooperation and joint plans with grid operators, e.g.

operator	Extra personnel BCM plans Emergency stockpiles	grid Additional production (e.g. private solar) within grid	sharing resources

4.2.4.2 Contextual case measures

Table 5 presents improvement measures specific to the three contextual cases.

Table 5. Contextual case improvement measures.

Measures to cope with electricity supply disruptions and contextual factors	
Contextual case	**Measures**
Grey zone	More personnel Training of personnel (including measures to reduce risk of absence due to fear) BCM plans Improved diesel supply for auxiliary power (own stockpiles, municipal or regional stockpiles, supplier agreements) Systems to improve surveillance of physical assets and system performance, when using auxiliary power
Heightened state of alert	Assigning personnel deployment duties within the CE Proactive coordination with armed forces (e.g. to avoid requisition of critical equipment)
War	Assigning personnel deployment duties within the CE Societal level (e.g. regional) stockpiles or other solutions for supply of diesel, spare parts, food, etc. Service agreements for repair services (e.g. electricians, other technicians) Joint BCM plans and improved coordination with interdependent actors

Takeaways (improvement measures)

- Almost all CEs rely on diesel-fuelled auxiliary power, and would benefit from improved fuel supply (e.g. regional stockpiles, supplier agreements, municipal coordination) or alternative auxiliary power solutions (e.g. solar, hydrogen).
- All CEs would benefit from more exercises, and improved BCM plans.
- All CEs would benefit from joint coordination with interdependent actors external to the CE.
- All CEs would benefit from improved supply solutions (e.g. for spare parts, consumables) by means of e.g. stockpile, service or supplier agreement, municipal coordination.
- For contextual cases, all CEs would benefit from assigning personnel deployment duties within the CE.
- For contextual cases, all CEs would benefit from improved staffing conditions (e.g. service agreements for repair-related expertise such as electricians).
- For contextual cases, all CEs would benefit from improved surveillance of critical assets.

4.2.5 Dependencies

All experts mentioned uncertainty and possible function loss from (inter)dependencies with actors external to the CE, especially for the contextual cases. This is well exemplified by the issues related to diesel supply (i.e. many CEs using auxiliary power simultaneously), deployment duties (i.e. several organisations relying on the same individuals), the drinking water CE relying on another supplier for 80% of the water, and the meal production expert's uncertainty on whether available food would be prioritised to them. Such dependencies might lead to greater function loss than shown in quantitative results, where only first-order effects on the specific CE were accounted for. The importance of dependencies is further exemplified in how many suggested improvement measures related to coordination with external entities, and higher-level pooling of resources. Based on suggested improvement measures, BCM plans paired with joint proactive preparation and societal-wide interdependency analyses seem suitable measures to minimise negative impact from cascading effects.

5 Discussion

This chapter includes a brief discussion regarding insights, applicability, and validity of the results and performed analysis, ending with suggestions for further research.

5.1 Key findings

Most of the results and analyses presented in 4 are best read in their detailed and specific form, as they are hard to generalise without losing some validity or usefulness. However, certain key findings can be synthesised from the specific takeaways:

- Function, variability, and uncertainty vary greatly between different CEs, underlining the need to evaluate disruption effects for specific CEs (or types of CEs), and the difficulty in giving general answers to how CEs are affected.
- All examined CEs are dependent on diesel and auxiliary power units to maintain function during prolonged electricity disruptions, except the wastewater CE which would install it if budget allowed.
- Examined CEs generally appear more vulnerable to outage length (hours/day) than scenario duration (number of days) – although variability and epistemic uncertainty generally increase with duration – indicating that minimisation of outage lengths might allow society to function relatively well even in prolonged scenarios.
- CEs are further strained by all three contextual cases, where staffing (e.g. retaining personnel, adequate skills and training) and supply flows (e.g. spare parts, diesel, repair materials, food) are uncertain factors risking significant impact on CE function.

Several improvement measures are common to all or most CEs, relating to similar vulnerabilities in the CEs. These include but are not limited to:

- improved supply solutions (e.g. stockpiles or supplier agreements for fuel, spare parts, consumables)
- BCM planning and joint coordination with interdependent actors to address cross-sectoral interdependencies
- improved staffing (especially assigning deployment duties within CEs, and service agreements for skilled labour like electricians)
- surveillance of critical assets during contextual cases.

An observation made during interviews with municipal crisis management experts was that cooperation and coordination with private actors were limited. There could be benefits to higher-level coordination of solutions to the common measures, as suggested by relevant authorities (SOU, 2021:25; MSB, 2022b). As mentioned in 3.6, deregulated CIs with distributed responsibility using contractual agreements have to some degree achieved high reliability levels in peace-time contexts. For more extreme situations where suppliers and service providers are strained, such as 90-day disruptions or in a context of war, it is imaginable that contracts cannot always be fulfilled. Perhaps it is possible to integrate the two approaches, where municipal or regional administration can help with joint coordination of supplier and service agreements for CEs, enabling contracts that realistically can be fulfilled in these situations. This way a CE might get more reliable supply of rare products (e.g. technical components), while still freely establishing agreements with local actors (e.g. farms).

Another observation to recognise in the context of Sweden's transforming energy system is potential synergy with the expansion of distributed intermittent electricity sources. Some CEs had installed solar panels, which could improve self-sufficiency if the installation can feed the CE during grid outage (e.g. using battery solutions), which is not always the case. Perhaps more interestingly, large-scale battery storage facilities at the city, municipal, or higher level were mentioned. These types of measures fall outside the direct scope of this thesis as outages are presupposed, but such facilities might reduce the impact from prolonged scenarios, especially for shorter outage lengths. If such supply was prioritised to CEs they might avoid outages altogether, even if significant disruptions affect other parts of society.

The methodology has shown potential as a means of measuring effects of electricity disruptions on CEs. It is conceivable that it can be applied for other types of disruptions as well, with adjustment to scenario conditions. The comparability between different CEs and experts is a strength, enabled by use of a simple measure isolating direct disruption effects, and avoiding too many undeclared assumptions about cascading effects, or speculation about end user consequences. Still, the qualitative arena afforded by the interview stage allows for nuancing to the rigid quantitative assessments. The methodology provides a solid base measure which potentially could be used for further analyses, e.g. quantifying societal or end user consequences based on the function level of the CE.

5.2 Generalisation

One should be careful trying to generalise from the results. Significant differences between CEs were identified and a limited number of CEs in a specific region were studied. Furthermore, municipal management results showed that assessments can vary substantially within a CE type. Many assessments include significant uncertainty. Results may be roughly indicative for the CE type, but then it must be considered what the type actually is – a municipal-level CE of a certain category may differ in resources and system design between a metropolitan or a rural municipality, for example. Nonetheless, the findings can be used as a starting point to build an understanding of CE performance during prolonged electricity disruptions. Many issues and suggested improvement measures were similar across CEs, as were certain dependencies, e.g. on diesel supply. Such similarities were especially prominent for electricity disruptions during the three contextual cases.

5.3 Validity

Quantitative results in this thesis do not fully account for cascading effects. Excluding higher-order effects successfully isolates and makes comparable first-order disruption effects on CEs, but risks underestimating total consequences. All limitations related to expert elicitation discussed in 2.2 must be considered. Standardisation using linear extrapolation has no effect if there is no interval (i.e. highest, best, lowest are the same). Special consideration should be given when interpreting such results, especially if original confidence levels were low. Reference to unstandardised results (see D) is recommended. Regarding statistical significance one might argue that including only one or two CEs of each type is insufficient. First, one should be careful regarding generalisation of these results, as described in 5.2. Second, as discussed in 2.2.1, it was a deliberate decision to avoid aggregation of expert assessments since it does not necessarily come closer to reality than outlier judgments. Attaining results from various CE types was of greater interest than several assessments for one specific type. Third, one could argue that most CEs are too distinct (e.g. the specifics of system design, available resources, local conditions) for aggregation to be suitable (i.e. from a statistical viewpoint it would be a sample drawn from different populations). It is still possible that aggregated results from a larger sample of each CE type would benefit higher-level resource prioritisation or decision-making. Aggregating several assessments for a specific CE might have increased accuracy but was not possible due to the low number of suitable experts.

5.4 Further research

Studies to evaluate the generalisability (e.g. within Sweden, or between different countries) of these types of CE assessments could help inform the adequate use of results from this thesis. Similar studies examining more CEs (varied in type, location, etc.) could help build a holistic picture of Swedish CE resilience. Studies using different methodology examining the same (or similar) CEs could help in two ways: first, by extending knowledge of disruption effects on those CEs, and second, by enabling further evaluation of reliability of results and methodological choices in this thesis. Further research to validate and better detail contextual cases (e.g. based on real cases such as Ukraine) could enable more realistic conditions for assessment. Potential usefulness of this type of study to cross-sectoral interdependency perspectives is worth exploring. Lastly, it would be very useful to study the effectiveness of proposed improvement measures, especially if applying some type of holistic cost-benefit perspective acknowledging relevant competing interests. Evaluating potential synergy effects with ongoing expansion of distributed intermittent electricity sources and related infrastructure (e.g. city-level battery storage facilities) would be particularly valuable.

6 Conclusions

This chapter presents general conclusions related to the thesis aim and research questions (defined in 1.3-1.4). 6.1-6.3 lists several distinct conclusions categorised by which research questions they relate to.

An overarching observation is that CEs seem more sensitive to the length of individual outages, and less sensitive to whether such outages reoccur during prolonged scenarios. Much can be won through simple measures like joint coordination between interdependent CEs – it costs little and can be implemented immediately. It is concluded that further analyses, in general research settings and practically within specific CEs, are required to successfully develop CE resilience and Swedish total defence capabilities. Regarding methodology, the approach employed by this thesis can provide a solid, easily comparable base measure for effects on CEs by different critical flow disruptions. This measure can be used for further analyses, e.g. quantifying societal consequences based on the function level of a given CE.

6.1 Effects on CEs

The following conclusions are drawn regarding research questions 1) and 3).

- Effects of up to three months electricity supply disruptions vary significantly across the 8 studied CEs, underlining that actionable information should be based on analysis of specific CEs (e.g. as presented in 4).
- CEs generally appear more vulnerable to outage length (hours/day) than scenario duration (consecutive days with given outage length), indicating that consequences are not necessarily worsened if disruptions are prolonged.
- Prolonged duration generally correlates with greater uncertainty, meaning actual consequences in these scenarios are harder to determine.
- All CEs rely on diesel auxiliary power units to maintain function during disruptions, highlighting diesel and spare parts dependence, except the wastewater CE which would install it if budget allowed.
- Cascading effects are challenging to account for but can have notable impact.

6.2 Contextual cases

The following conclusions are drawn regarding research question 2).

- If electricity disruptions occur combined with contextual cases (grey zone, heightened state of alert, or war) instead of peace-time conditions, CEs are

further strained, where adequate staffing and supply flows are the most critical factors risking impact on CE function.
- All CEs risk losing personnel if deployment duties are inadequately assigned.

6.3 Possible improvement

The following conclusions are drawn regarding research question 4).

- Many measures are unique to specific contexts or conditions, underlining that improvement efforts should be based on analysis of specific CEs.
- Some types of improvement measures are common to all or most examined CEs, relating to similar vulnerabilities in the CEs. These include:
    - Improved supply solutions (e.g. stockpiles or supplier agreements for fuel, spare parts, and consumables)
    - BCM plans and joint coordination with interdependent actors (e.g. increased cooperation between municipality and private entities, joint supplier agreements)
    - improved staffing (e.g. service agreements for skilled labour, more personnel, adequate deployment duties)
    - alternatives to diesel auxiliary power.
- Potential synergies with ongoing expansion of distributed intermittent electricity sources (e.g. solar panel installations within CEs, city-level battery storage facilities) should be explored.

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A Scenarios & cases

In this appendix the outage scenarios and contextual cases are defined, along with conditions and assumptions.

Basic outage scenarios

Table 6. Basic outage scenarios for survey study.

SCENARIO VARIABLES \ SCENARIO	1	2	3	4	5	6	7	8	9
Total duration [days]	7	7	7	30	30	30	90	90	90
Outage length per 24h-day [hours]	2	12	24	2	12	24	2	12	24

SCENARIO VARIABLES DESCRIPTION

- **Total duration:** Number of consecutive days during which outage length occurs.
- **Outage length per 24h-day:** Number of hours per day during which there is electricity outage.

CONDITIONS & RAMIFICATIONS FOR ALL SCENARIOS

- A certain number of hours of electricity outage per 24h-day
- A certain number of consecutive days with the same number of outage hours
- Outage hours can occur any time during the 24h-cycle (morning, day, night, etc.)
- It is not known in advance when the hours occur (unplanned outage)
- During these hours there is complete outage on the electricity grid
- During the hours with electricity outage your organisation can only use electricity if it is supplied through the organisation's own resources (e.g. reserve power and diesel, UPS systems, batteries, etc.)

NOTE: Except for electricity supply, assume all other societal functions (e.g. transports, medical care, etc.) work as usual. This means **assessments are only to account for disruptions in electricity supply**. Do **not** account for how you think other important societal functions are affected by the electricity disruptions.

Contextual case 1: Grey zone

Based on case 5 of FOI (2018).

Generally

- The sequence of events is prolonged and escalating over 9 months.
- The case is characterised by the challenges of managing disruptions, clarifying the situation, restoring societal function, mitigating negative effects of disruptions, etc.

- Anxiety and fear spreads in society, which can for example increase sick leave.
- Disinformation and other actions affect trust in governance.

Initial phase

- Larger number of unexplained accidents occur. Burden on emergency responders and medical services.
- Minor cyber-attacks and physical sabotage on societal functions, such as local supply systems, individual companies, or other actors.
- Distorted information and corrupted data spread within IT systems of different actors.
- Public trust in authorities and politicians declines.

Second phase

- Several months of infrastructure disruption takes its toll: businesses reach overtime ceilings, run out of spare parts, exceed budgets. Decisions by authorities are delayed.
- Periodic disruptions to local and regional electricity supply and data/telecom systems contribute to further disruption of other societal functions.
- Shortages of some foodstuffs due to hoarding. Cash shortages. Local outbreaks of stomach flu. More fires due to increased use of open fires/fireplaces for cooking. Organized crime, heavily armed criminals and violent clashes are increasing.
- Banking/financial sector exposed to cyber extortion.
- False press releases from Swedish Security Service about increased terrorist threats are spread in social media.

Final phase

- After 6 months, influence operations to sow division and disinformation increase.
- Supply of goods deteriorates as sabotage takes place against ships and shipowners begin to avoid the Baltic Sea. Production in some manufacturing industries has already stagnated.
- Distribution of fresh and frozen food is deteriorating.
- Major cyber-attacks.
- Major disruptions to national infrastructure.
- Pressurizing measures (home visits, emails) on key personnel in private and public CEs.
- After 9 months of disruption, fear is widespread. Some people leave the cities and move to holiday homes in the countryside. Some leave Sweden. Partly because an acute food shortage can be discerned. Rationing is prepared, prices and hoarding escalate. Some outbreaks of violence.

- Many help each other and some are prepared to protect their own resources by force.

Contextual case 2: Heightened state of alert

Based on case 1 of FOI (2014).

Generally

- The government enacts a heightened state of alert. An attack on Sweden is not happening but may be imminent.
- The military defence must be mobilised in a very short time. In parallel, the civilian defence must take its measures in the event of a high level of preparedness. These two together entail considerable strain on society, especially management functions.
- The mobilisation of the Armed Forces requires resources to a large extent from civilian actors. This includes things like refuelling, food, shelter, purchase and requisition of supplies (e.g. vehicles, food, fuel, hygiene items, batteries, computers).
- Preparatory measures to be able to deal with a military attack on Sweden must be taken by all total defence actors.
- The decision on heightened alert and mobilisation of the Armed Forces is interpreted by parts of the population as that war is imminent, which causes some spontaneous evacuation, hoarding of supplies, traffic jams, financial turmoil, large cash withdrawals, etc. Some of your staff may not come to work.
- The urgent mobilisation of the Armed Forces displaces civilian needs for means of transportation and supplies (e.g. trucks and drivers are taken out of civilian traffic to instead drive for the Armed Forces).
- Accessibility on some roads and railways is temporarily reduced.
- Foodstuffs and diesel fuel in supermarkets and gas stations along major transportation routes are reserved for the Armed Forces.
- If local or regional planning for mobilization is not known and exercised by the civilian actors whose help is needed, the situation can become chaotic and cause significant problems on the civilian side.

Contextual case 3: War

Based on case 2 of FOI (2014).

Generally

- An attacker targets civilian objectives such as electricity supply, telecommunications, transportation systems, etc., making repairs difficult. Prolonged course of events.
- Difficult to predict which areas will be affected next, and therefore at risk.
- Nationwide information system only partially functioning, limited possibilities to reach the public with information is limited.
- Direct and indirect effects of infrastructure destruction affect society.
- Damage and losses among the civilian population occur gradually.
- Electronic communications (telephone, internet), energy supply and transportation are affected to varying degrees throughout the event.

Initially

- Minor attacks on municipal technical supplies municipalities are forced to prioritise.
- Sabotage groups and cyber-attacks cause local interruptions to electricity, telecommunications and IT systems.
- Accidents in the form of explosions and breakdowns are staged.
- Targets are scattered throughout the country. Metropolitan areas are slightly more vulnerable.
- Interruptions in municipal technical supply (water, sewage, district heating) affect individual municipalities. Vulnerable municipalities need different types of external support.
- Uncertainty spreads in society, making communication and management difficult.

Subsequently

- Attacks shift to more open attacks and a faster sequence of events. Long-range means of warfare (e.g. cruise missiles), drone strikes, cyber-attacks and sabotage groups are used against key societal functions.
- After 3-5 days of these overt attacks, a heightened state of alert is prepared. At this point, the attacks also extend to symbolic and politically important targets.
- Major disruptions in communications and electricity supply.
- Backup power is used by many actors and the supply of fuel for it becomes unreliable due to the high demand.
- The transportation sector with distribution and supply of various goods is affected and priorities must be set against the needs of civil and military defence.
- All electricity, telecommunications and IT-dependent activities are affected by various interruptions in information, management, payment systems, distribution systems.

- The health care system can be overloaded with mass casualty events. Through prioritisation health care function can be maintained. Dependent on fuel supply for backup power.
- Public administration works but is strained. Important decisions can be misinterpreted or stuck in the decision-making chain.

B Interview guide

Introduction

- Ensure consent for recording.
- Ensure that recording is up and running.
- Ensure that the interviewed expert has read selected assessments from other experts.
- 'Describe very briefly your CE and its role in maintaining vital societal functions.'

Part 1: Survey questions

- 'Looking back, do you think of anything related to how you made your assessments, that you want to bring up?'
- 'How did you reason when assessing your confidence levels?'
- 'Do you want to add anything about assumptions?'
- 'Do you want to change any assessment?'
    - Record changes in separate spreadsheet
        - Which scenario
        - Which question
        - The new value

Part 2: General qualitative questions

- 'Do you have a limit on how long interruptions in your operations are acceptable, or how much of your normal function must be maintained? Both based on internal objectives/requirements, and external requirements such as legislation.'
- 'What type of measures could improve your ability in coping with prolonged electricity supply disruptions?' (examples: organisational, planning, resources, exercises, etc.).
- 'What internal measures could you implement (or have you already implemented) with existing resources to improve your ability in coping with prolonged electricity supply disruptions?'
- 'What external actions or resources do you consider most important to improve your ability to cope with prolonged electricity supply disruptions?' (examples: planning support, changes in legislation, services/resources from other organizations, decisions higher up in the organization, etc.)
- 'What cooperation or coordination could improve your ability to cope with prolonged electricity supply disruptions?'

Part 3: Contextual cases

- 'How would your assessments change if contextual case *grey zone* applied?'
    - 'How can your ability to maintain function in the contextual case be improved?'
- 'How would your assessments change if contextual case *heightened state of alert* applied?'
    - 'How can your ability to maintain function in the contextual case be improved?'
- 'How would your assessments change if contextual case *war* applied?'
    - 'How can your ability to maintain function in the contextual case be improved?'

C Survey

The questions included in the survey, which was in Swedish, are presented in English in Table 7. The scenario-related questions were all asked once for each outage scenario. All questions were preceded by information about how the survey was to be performed, definitions of important terms (e.g. CE), and conditions applying to outage scenarios, as presented in Table 6. Survey results were downloaded in PDF and Excel format, and were also registered manually in a second, separate Excel file.

Table 7. Survey questions.

Question	Question type	Alternatives
State what type of organisation you represent (e.g. harbour, municipal meal production)	Open textbox	
What overarching societal function would you say your organisation contributes to most?	Closed pre-coded	The 10 civil preparedness sectors
State which specific function your organisation has, that contributes to maintaining an overarching societal function (e.g. public transport in Lund municipality, emergency care in Scania). Be as specific as possible.	Open textbox	
How many percent of your normal function can be maintained in outage scenario X: Realistically, what do you assess to be the lowest reasonable value?	Closed pre-coded	0%, 5%, ..., 95%, 100%
How many percent of your normal function can be maintained in outage scenario X: Realistically, what do you assess to be the highest reasonable value?	Closed pre-coded	0%, 5%, ..., 95%, 100%
How many percent of your normal function can be maintained in outage scenario X: Realistically, what is your best	Closed pre-coded	0%, 5%, ..., 95%, 100%

assessment of the value?		
How confident are you that your interval, from lowest to highest, can capture the real value for outage scenario X?	Closed pre-coded	0%, 10%, ..., 90%, 100%
If the electricity outages were planned (i.e. getting information beforehand which times in a given day when outage will occur), how would your assessment change for scenario X?	Closed pre-coded	Better function Same function Worse function
Describe any assumptions you made while performing the assessments (e.g. about the situation in society, cooperation with other actors)	Open textbox	
Is there anything specific you want me to know when interpreting the answers you have given in this survey?	Open textbox	

D Outage scenario results

In this appendix, raw results for outage scenarios are presented. It includes changes made during the interview.

Table 8. Unstandardised survey assessments.

Changes made during interview marked red

EXPERT I.D.	ORGANISATION	SPECIFIC FUNCTIONALITY	QUESTION	SCENARIO 1 2h/day 7 days	SCENARIO 2 12h/day 7 days	SCENARIO 3 24h/day 7 days	SCENARIO 4 2h/day 30 days	SCENARIO 5 12h/day 30 days
1	Municipal meal production	Meal supply for schools, preschools, special accommodations	Lowest reasonable	80%	25%	20%	80%	15%
			Highest reasonable	100%	75%	55%	100%	65%
			Best assessment	90%	55%	50%	90%	50%
			Confidence in interval	100%	80%	50%	90%	80%
			If planned outage	Better	Better	Same	Better	Better
2	Fiber network operator	City fiber network	Lowest reasonable	75%	10%	0%	65%	5%
			Highest reasonable	85%	15%	0%	75%	10%
			Best assessment	75%	10%	0%	75%	5%
			Confidence in interval	90%	90%	100%	90%	90%
			If planned outage	Better	Same	Same	Same	Same
3	Rescue services	Municipal rescue services (as per the law on Protection against accidents)	Lowest reasonable	100%	100%	100%	100%	100%
			Highest reasonable	100%	100%	100%	100%	100%
			Best assessment	100%	100%	100%	100%	100%
			Confidence in interval	100%	100%	100%	100%	100%
			If planned outage	Same	Same	Same	Same	Same
4	Municipal management (1)	Municipal crisis management (1)	Lowest reasonable	100%	95%	70%	100%	90%
			Highest reasonable	100%	100%	80%	100%	95%
			Best assessment	100%	95%	75%	100%	95%
			Confidence in interval	100%	100%	80%	100%	90%
			If planned outage	Same	Same	Same	Same	Same
5	Municipal management (2)	Municipal crisis management (2)	Lowest reasonable	80%	50%	40%	85%	50%
			Highest reasonable	100%	100%	75%	100%	90%
			Best assessment	90%	60%	50%	90%	70%
			Confidence in interval	80%	70%	60%	80%	70%
			If planned outage	Better	Better	Better	Better	Better
6	Wastewater utilities	Wastewater management	Lowest reasonable	50%	5%	0%	20%	75%
			Highest reasonable	80%	50%	0%	80%	80%
			Best assessment	80%	20%	0%	75%	75%
			Confidence in interval	80%	60%	100%	60%	60%
			If planned outage	Better	Better	Same	Better	Same
7	Drinking water utilities	Drinking water supply (production & distribution)	Lowest reasonable	80%	80%	70%	65%	70%
			Highest reasonable	95%	95%	85%	90%	90%
			Best assessment	90%	90%	85%	85%	85%
			Confidence in interval	90%	90%	80%	70%	70%
			If planned outage	Better	Better	Better	Better	Better
8	Electricity distribution operator	Local distribution grid	Lowest reasonable	20%	20%	10%	20%	10%
			Highest reasonable	20%	20%	10%	20%	10%
			Best assessment	20%	20%	10%	20%	10%
			Confidence in interval	30%	30%	30%	30%	30%
			If planned outage	Better	Better	Same	Better	Same

SCENARIO 6		SCENARIO 7		SCENARIO 8		SCENARIO 9			
24h/day	30 days	2h/day	90 days	12h/day	90 days	24h/day	90 days	ASSUMPTIONS	ADDITIONAL INFO
10%		80%		15%		10%		Working reserve aggregates for 3 cooking kitchens.	
50%		100%		65%		50%			
60%		90%		50%		60%			
80%		90%		70%		70%			
Better		Better		Better		Same			
0%		60%		5%		0%		End customers (mobile phone sites, total defence, prioritised customers) have own battery backup.	6h outage is vital point. After that controlled shutdown must be started.
0%		70%		10%		0%			
0%		60%		5%		0%			
100%		90%		90%		100%			
Same		Same		Same		Same			
100%		100%		80%		70%			
100%		100%		100%		90%			
100%		100%		90%		80%			
100%		100%		80%		70%			
Same		Same		Better		Better			
70%		100%		85%		70%		That reserve power was working. Somewhat hard to get fuel in longer timeframe.	
85%		100%		90%		85%			
85%		100%		90%		75%			
90%		100%		90%		70%			
Same		Same		Same		Better			
20%		90%		30%		20%		More days -> Develops habit, becomes "new normal" with less negative effect. 90 days hard to imagine.	
70%		100%		75%		60%			
50%		95%		50%		50%			
60%		80%		60%		50%			
Better		Better		Better		Better			
0%		20%		50%		0%		No access to reserve power.	
0%		80%		50%		0%			
0%		75%		50%		0%			
100%		70%		100%		100%			
Same		Better		Same		Same			
75%		50%		45%		70%		Watering ban. Request public to save water if longer disruptions.	80% delivered from external actor. Boiling rec. if quality parameters not met.
85%		85%		85%		85%			
80%		70%		70%		80%			
60%		50%		50%		70%			
Better		Better		Better		Better			
10%		10%		10%		5%		Scenarios with complete outage (24h/day) very hard to assess.	
10%		10%		10%		5%			
10%		10%		10%		5%			
20%		30%		30%		30%			
Same		Same		Same		Same			

E Civil preparedness sectors

Table 9. Civil preparedness sectors.

Civil preparedness sector (Sector-responsible authority)	**Vital societal functions and types of actors**
Economic security (Swedish Social Insurance Agency)	Economic safety for families and children; social insurance, unemployment insurance; pensions. Generally maintained by public or state actors.
Electronic communications and postal services (Swedish Post and Telecom Authority)	Carrier services; basic systems for net communications; infrastructure for electronic communication; traceable time and frequency; delivery of letters and parcels. Generally maintained by private operators.
Energy supply (Swedish Energy Agency)	Production and transmission of electricity; electricity trade; production and distribution of district heating and district cooling; production (processing) of fuel and propellants; production and distribution of gas; production and distribution of solid fuels; auxiliary power for VSFs. Generally maintained by private companies in different markets.
Financial services (Swedish Financial Supervisory Authority)	Mediation of payments; transforming savings to financing; risk management of financial services. Generally maintained by private companies, with central tasks maintained by state authorities.
Basic data (Swedish Tax Agency)	Supply of basic data on persons, companies, properties, geographical information and positioning. Generally maintained by public actors.
Health, medical care, and welfare (National Board of Health and Welfare)	Health and medical care; dental care; disease control; medicine supply; social services. Generally maintained by public actors such as regions and municipalities.
Food supply and drinking water (National Food Agency)	Primary production of food and animal feed; production, distribution, and sales of food; cooking of food in commercial kitchens; safe foods including drinking water; disease control and safe disposal; animal health and medical care; drinking water supply; sewage; waste management (primarily municipal waste). Generally maintained by private companies and municipalities.

Public order and security (Swedish Police Authority)	Policing; border protection and monitoring; prosecution activities; correctional treatment; surveillance and security activities. Generally maintained by public actors with some private companies conducting surveillance and security.
Transport (Swedish Transport Administration)	Air transports (air traffic, airports, operators); sea transports (sea traffic information, ports, safe sea routes; operators); road transports (traffic control, roads, operators); railway transports (traffic control, railways, stations, operators); public transport (operators); terminals (reloading). Generally maintained by private companies.
Civil protection (Swedish Civil Contingencies Agency)	State and municipal rescue and emergency services; alarming services; population protection; information on weather, water, and climate; radiation protection preparedness. Generally maintained by municipalities and state authorities.