Resilience Beyond Technical Systems

Designing a framework for assessing resilience in the energy sector

H.B. Vreeswijk

MASTER OF SCIENCE

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by

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"You never change things by fighting the existing reality.
To change something, build a new model that makes the existing model obsolete."

-R. Buckminster-Fuller

Abstract

Organisations in the energy sector increasingly face complex disruptions and long-term stresses that threaten their ability to deliver essential services. While resilience has emerged as a key concept for addressing such challenges, it remains conceptually fragmented and methodologically inconsistent, particularly within the context of critical entities more commonly known by their previous terminology, critical infrastructures. This study addresses this gap by developing a framework for assessing resilience in the critical entity energy.

Using a Design Science Research (DSR) approach, the research integrates theoretical insights from resilience literature with empirical input from industry observations and semi-structured interviews. First, a systems-oriented definition of resilience is established. Subsequently, relevant resilience criteria and indicators are identified and structured into a multi-criteria assessment framework, grounded in the Technical, Organisational, Social, and Economic (TOSE) dimensions, which have been identified as the aspects of resilience.

The resulting framework, with its four aspects, comprises 19 criteria and 89 indicators. Enabling organisations to systematically evaluate their resilience across interconnected aspects, thereby supporting strategic and operational decision-making in asset-intensive energy systems. Evaluation through expert interviews confirms the framework's relevance, novelty, and usability, highlighting its potential to translate the abstract concept of resilience into a comprehensive practical approach.

The resulting framework aims to provide a structured, transferable, and practice-oriented approach to resilience assessment for critical energy entities. A mechanism for continuously reviewing, expanding and refining that list, as the risks and vulnerabilities evolve.

Keywords: resilience, assessment, framework, critical entity, energy.

Contents

Acknowledgements

The process of writing a master's thesis has its ups and downs.
I still remember my first review after the first exam of MoT. Many answers for which I had not received any points, but after seeing the answer model, I thought, 'Yeah, I said the same thing, I just used fewer words to express it.' This work feels a bit like that too; talking about it is a lot easier than putting it into writing.

Firstly, I would like to thank Aad and Ellen for their commitment and guidance in this project. A phrase that passed by in our conversations, which I would also like to share with the audience, is: "You are not going to write a world-changing thesis; you are contributing to the literature, and others can respond to it". This helps a lot to put everything into perspective and therefore also to be able to say that this is not part of the scope or not possible in this timeframe.

Thanks to close friends for listening to my whining and providing the pep talks I needed. Having an emotional outlet and at the same time providing a critical and thoughtful input is extremely useful for organising your thoughts and realising that everything will be alright.

Colleagues from OHROS Consulting Group, thank you for the pleasant working atmosphere and insights you have shared during this period. With special thanks to Ennio and Ed for their support and guidance.

I'm happy everything worked out, not completely according to the planning I made in the beginning of this project, but within the preset timeline. Thanks to my friends at MOT, who made this master's program much more fun.

Hein Vreeswijk
Amsterdam, February 2026

Nomenclature

CE	Critical Entity
CER	Critical Entity Resilience
CI	Critical Infrastructure
CMMI	Capability Maturity Model Integration
DR	Design Requirement
DRS	Design Science Research
EEA	Electricity Engineers' Association of New Zealand
IEEE	Institute of Electrical and Electronics Engineers
ITAMS	International Transmission Asset Management Study
MCA	Multi-Criteria Analysis
MoT	Management of Technology
TOSE	Technical, Organisational, Social, Economic
TSO	Transmission System Operator
4Rs	Robustness, Redundancy, Resourcefulness, Rapidity
SSE-CMM®	Systems Security Engineering Capability Maturity Model

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Summary

Problem context
Organisations in the energy sector increasingly operate under conditions of profound uncertainty caused by geopolitical tensions, climate change, ageing infrastructure, regulatory pressure, and growing societal dependence on reliable energy services. Although resilience has become a central concept for addressing these challenges, its practical application remains hindered by conceptual fragmentation, inconsistent definitions, and the absence of comprehensive assessment methods. Particularly in the energy sector, which is determined as a critical entity and asset-intensive industry, thereby increasing complexity. Existing approaches tend to be sector-specific, narrowly focused, or insufficiently operationalised, leaving organisations without a coherent basis for strategic and operational resilience management.

Research Approach
This thesis addresses this gap by developing a structured and transferable framework for assessing resilience in critical energy entities. Using a Design Science Research (DSR) methodology, the study integrates theoretical insights from literature with empirical input from industry observations and semi-structured interviews with academia and industry experts.

First, a system-oriented definition of resilience is established by clarifying resilience of what, to what, and what resilience is within the context of critical energy systems. Subsequently, relevant resilience criteria and indicators are identified through systematic literature analysis, industry observations from the International Transmission Asset Management Study (ITAMS), and interviews. These elements are organised into a hierarchical multi-criteria framework structured around the four interrelated TOSE aspects: Technical, Organisational, Social, and Economic.

Results and Discussion
The resulting framework comprises four resilience aspects, 19 criteria, and 89 indicators, providing organisations with a comprehensive and structured tool for evaluating resilience across interconnected system dimensions. The framework is structured into a coherent hierarchical architecture in accordance with the methodology employed in the design of the framework. This did not align with the previously established requirements. Consequently, the framework is complemented by a Venn-based structure that explicitly visualises the interconnected and mutually reinforcing characteristics of resilience. This representation supports understanding by illustrating that resilience aspects and criteria cannot be assessed in isolation, but should be

considered as an integrated whole, as many of them influence and reinforce each other.

Evaluation through expert interviews confirms the framework's relevance, novelty, and practical applicability, demonstrating its capacity to translate the abstract concept of resilience into a concrete instrument. The framework enables organisations to systematically identify vulnerabilities, support strategic and operational decision-making, and embed resilience thinking into everyday practice. By offering a structured yet adaptable assessment approach, this research contributes both academically and practically to advancing resilience management within critical energy entities.

Implications
This research provides both theoretical and practical implications. Academically, it contributes to the resilience literature by translating the abstract and fragmented concept of resilience into an operational, multi-dimensional assessment framework. Organisationally, the framework's primary value lies in its ability to facilitate organisational dialogue and embed resilience thinking into everyday decision-making. By offering a shared language and structured representation of resilience, the framework aligns strategic, operational, and technical perspectives, supports consensus-building, and enables organisations to identify vulnerabilities in a context-sensitive manner. In addition, the framework enables organisations to systematically evaluate their resilience across interconnected aspects, thereby supporting strategic and operational decision-making in asset-intensive energy systems.

1

Introduction

1.1 Problem Introduction

In today's fast-moving technological environment, organisations face the pressure to continuously adapt and innovate to stay ahead of the competition and maintain their operational performance [52]. Organisations face the challenge of managing their operations in a way that consistently meets expectations.

The landscape is changing repeatedly, and organisations are confronted with a combination of external disruptions and internal vulnerabilities. Examples include natural hazards, the electronic chip shortage originating in Taiwan, raw materials from Ukraine, pandemic disease, the disruption of supplies during the Suez Canal blockade, and the Russian boycott of gas. At the same time, internal challenges, including staffing shortages, regulatory bottlenecks, and ageing infrastructure, further undermine the ability of organisations to anticipate, absorb, and recover from disruptions.

Given these examples, organisations are increasingly seeking ways to strengthen their position and operations for both near- and long-term planning. In this trend, the focus on Strategic Asset Management has increased. Asset management helps to find a balance in performance and operations (cost and risks). The ISO55000 defines asset management as "Coordinated activity of an organisation to realise value from assets. Asset management maturity is key to enhancing an organisation's performance" [65]. However, having your asset management strategy in order is not sufficient in the current social, technological, and political climate.

It is for this reason that companies are seeking to identify the subsequent phase in their development. This process is often described in terms of enhancing resilience, enabling firms to withstand shocks while maintaining their competitiveness in the market [60]. OHROS Consulting Group primarily advises organisations in the energy sector, particularly asset-intensive companies that must make critical asset decisions in an era of unprecedented change. OHROS observes that the sector is increasingly asking how organisations can enhance their resilience. The Institute of Asset Management published in July of 2025 a Good Practice Guide For Improving Resilience [9]. The first step they introduce is assessing resilience. Resilience assessment has become a key aspect in providing alternative ways of thinking about and practising management [19]. At the same time, it is recognised that the tools and methods needed to support such resilience-oriented decision-making are not yet sufficiently developed [10]. The industry has shown a growing desire to translate resilience from an abstract concept into operational tools, beginning with clearer definitions of resilience and the development of maturity-based assessment models for the energy sector [9]. These efforts directly support the shared goal of reducing the likelihood and impact of blackouts. The societal relevance of this objective has become more apparent e.g. Europe, where increased public attention to emergency preparedness highlights broader concerns about energy system disruptions.

1.2 Problem Statement

In recent years, there has been an increase in research focusing on resilience [63]. This phenomenon is inextricably associated with the crises and turbulence that have characterised recent years. Another factor to consider is the increasing global integration of the world, which signifies that individuals are no longer solely dependent on their local environment. The problem addressed in this research is that resilience remains conceptually fragmented and methodologically inconsistent.

This study focuses on a sector that is considered critical, with a specific focus on the energy sector. In 2008, the European Union (EU) defined critical infrastructure as follows: "Assets, systems, or parts of systems that, if disrupted or destroyed, would have a significant impact on citizens of member states." These needs are referred to as economic health, safety, and social well-being [26]. Later in 2022, the EU came up with a more refined definition that focuses more on infrastructures and divides them into critical entities (CE) that provide essential services and whose disruption could have wider societal impacts [27]. The Directive identifies eleven key sectors: energy, transport, banking, financial infrastructures, health, water, digital infrastructures, public administration, space, and food production. In addition to identifying the sectors concerned, the act also imposes further restrictions that companies within these sectors must comply with in order to ensure that they are able to continue to function at all times. Europe is not the only region focusing on this, other regions are also undertaking initiatives to organise the security of critical entities (e.g. the US, UK, China, Chile, Australia) [21].

The energy sector is also an asset-intensive industry. Asset-intensive industries are sectors that rely on significant capital for expensive, high-value physical assets. Characteristics are: high capital investment, dependence on physical assets, focus on asset management, complex and often harsh operating environments, and long asset lifecycles [43]. These characteristics introduce additional challenges for organisations operating in the energy sector, thereby reinforcing the critical importance of resilience. Resilience has emerged as a crucial concept for ensuring that utilities can continue delivering essential services under uncertainty. According to Oliveira Teixeira et al., resilience thinking should no longer be viewed solely as a defensive or reactive measure. Instead, it needs to be embedded in the everyday activities of an organisation, transforming into a best practice that also helps prevent minor, non-disastrous problems [52].

Resilience is multidimensional, which means that various factors influence the resilience of a system (e.g. physical, environmental, social). Existing frameworks offer different lenses on resilience. Effective frameworks would recognise the interdependency of these factors and provide systematic ways to evaluate resilience. One of the key challenges in addressing resilience arises from the fact that existing methods are based on diverse and sometimes conflicting inputs.

An early form of assessment framework was developed by Cutter et al. named the Disaster Resilience of Place (DROP) [22]. It focuses not only on pre-event risk reduction but also on post-event response. The assessment benchmarks a community's resilience before a disaster (as a baseline) and measures how interventions change that baseline or speed up recovery. DROP is used to develop Baseline Resilience Indicators for Communities (BRIC) index [21]. BRIC has a focus on communities and has 49 indicators into six broad resilience components to measure the system resilience. It gives a practical outline on how an assessment can be done for communities.

Heinimann et al. introduce a resilience management framework based on the ISO standard 31000, a risk management and assessment framework that is widely accepted. Accordingly, the risk management process consists of five activities: (1) establishing the context, (2) risk identification, (3) risk analysis, (4) risk evaluation, and (5) risk treatment [32]. It looks at an infrastructure system as an integration of engineered components, the operating organisation, and the user subsystems. From an asset management perspective, the IAM Resilience Cycle emphasises risk-based thinking, focusing on low-probability, high-consequence events. However, it primarily provides tools for identifying resilience criteria rather than defining or operationalising resilience itself [9].

Many frameworks are sector-specific [62, 57, 69], while these offer valuable insights into quantification methods [50], they lack transferability across domains. Even comprehensive reviews, such as Babu et al., acknowledge persistent research gaps, including the absence of a universal definition and the limited integration of socio-economic factors in resilience assessments [11].

Similarly, frameworks emphasise socio-economic interdependencies, reinforcing the need for a broader, system-level perspective [68]. Recent works propose alternative key performance indicators and dimensions of resilience [5, 58], yet these remain heterogeneous and context-dependent, underscoring the lack of standardised criteria for resilience assessment across sectors. Now, resilience is an umbrella concept, a term with different meanings and approaches [14]. While many existing frameworks are predominantly qualitative, the past five years have seen a growing number of quantitative studies. However, many quantitative studies are often not aligned with broader contexts or are so case-specific that they cannot be applied in a replicable manner [47]. This underscores the need to revisit the underlying foundations, which requires a clear conceptual foundation at a qualitative level. With a perspective that extends beyond purely technical elements to include organisational and other systemic components, aligning closely with asset management strategies.

1.2.1 Knowledge Gap

Both practitioners and scholars emphasise the need to make resilience measurable. A necessary step in enhancing resilience is therefore to identify where to focus, which underscores the importance of measuring and assessing resilience [60]. At the same time, the concept of resilience lacks a shared consensus on it's definition [6]. Together, these issues contribute to fragmentation in both research and practice, making it difficult to establish a systematic approach to assessing and enhancing resilience.

Although an increasing number of studies have been conducted in recent years, the majority of studies on existing CE resilience (assessments) have several common limitations, partly building on the issues identified earlier in this section. To begin, much of the research focuses on conceptual definitions of resilience; however, there remains vagueness, which hinders the development of generalizable indicators and criteria for its assessment [6, 30]. While scholars emphasise the importance of resilience, few provide practical tools or guidance for applying the concept at operational or strategic levels within organisations [24]. The majority of resilience assessment studies tend to concentrate, focusing on one single or a couple of aspects of (CE) resilience, but don't provide the complete picture [73]. Existing frameworks are case-specific, making them not generalisable [45]. The main challenge seems to be to develop a common set of indicators for cross-comparison. Research is required to address the quantification and measurement of resilience in all its interrelated dimensions [63], but without the right foundation, the quantification is ineffectual.

The central research gap, therefore, lies in the absence of a universal definition of resilience. As a result, no integrative and operationally applicable assessment framework—one that connects conceptual understandings to practical management—currently exists for the critical entity energy.

1.3 Research Objectives

Building upon the problem statement provided in the previous section, the main research question of this thesis is:

> **How can organisations in the critical entity, energy, perform a comprehensive resilience assessment?**

In order to provide more structure to the main research question, five sub-questions have been formulated for this study.
SQ1 focuses on understanding the definition of resilience in the context of the scope:

> SQ1: *What does the term resilience mean for critical entity energy?*

SQ2 focuses on the exploration of the development of a resilience framework:

SQ2: *What do industry stakeholders consider important when developing a resilience framework?*

When the definition is clear, the identification of relevant criteria and indicators to be considered when assessing resilience will be carried out, leading to SQ3:

SQ3: *Which criteria and indicators can be identified to assess the aspects of resilience?*

The first three sub-questions focus on the generation of new information, SQ4 deals with organising this information into a framework:

SQ4: *How can the criteria be structured into a practical multi-criteria resilience framework?*

Finally, the evaluation of the framework in the industry is examined in SQ5:

SQ5: *How does the proposed framework enable a comprehensive resilience assessment for organisations within critical energy entities?*

1.4 Management of Technology perspective

The assessment of resilience connects to the program of Management of Technology (MoT) as it addresses the strategic management of complex, technology-intensive organisations under uncertainties. By developing a resilience framework, organisations can use the knowledge to maximise customer satisfaction on the one hand, while maximising corporate productivity, profitability, and competitiveness on the other. This approach provides decision-makers (managers) with structured support for defining strategies to address technological, organisational, and geopolitical challenges.

1.5 Structure of the thesis

This thesis is organised into six main chapters that together address the research objective and answer the central research question.
Chapter 2 presents the research methodology, outlining the overall research design, data collection methods, and analytical approach.
Chapter 3 provides the analytical foundations and empirical input used to construct the resilience framework.
Chapter 4 documents the framework development process, detailing the design decisions and iterative refinement activities.
Chapter 5 demonstrates the application of the framework and presents the resulting evaluation outcomes.
Finally, Chapter 6 synthesises the findings and formulates a coherent answer to the research question, reflecting on the study's contributions and implications.

2
Research Methods

This chapter outlines the methodological approach of the study. It introduces Design Science Research (DSR) as the methodological foundation for designing the framework and details the DSR process used to operationalise the three interconnected cycles into structured steps and phases. Furthermore, the chapter establishes the data collection strategy for each phase and describes the methods used.

2.1 Research Approach

The main prospect of this study lies in its potential to advance CE resilience assessments in ways that are directly useful for practical operational decision-making. Figure 2.1 illustrates two primary approaches described in the literature by Kott et al. to measuring resilience. Model-based approaches use system configuration modeling and scenario analysis to predict system evolution. Metric-based approaches use measures of individual properties of system components or functions to assess overall system performance [44]. Multiple tools have been developed to address resilience in systems in both methodological groups. For this research, indices/indicators is the preferred method. Mainly because this can then contribute to determining a common set of indicators, which is currently a gap in the literature, as described earlier. Moreover, this approach avoids the occurrence of a case-specific outcome, which is often observed when model-based methods are employed, thereby decreasing the sectoral applicability of the process. The indicators will be developed using a structured approach, ensuring both the academic basis and practical application of the indicators are facilitated.

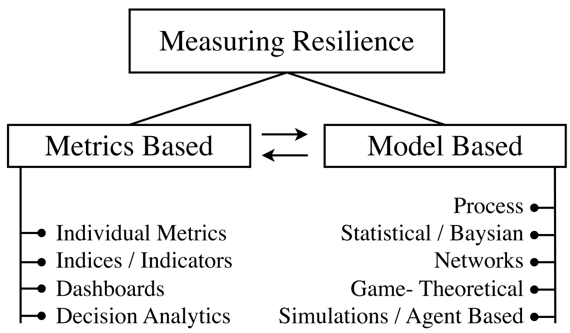


Figure 2.1: Approaches for resilience assessment (Kott et al.)

2.2 Design Science Research

In constructing this framework, the study follows a Design Science Research approach. Design Science Research (DSR) is fundamentally concerned with discovering what is true in order to create what is effective. At its core, DSR seeks to extend the boundaries of scientific knowledge through the design and development of artefacts [36]. This is achieved through three interconnected cycles (figure 2.2).

- Relevance Cycle - connects the research to the environment (industry, stakeholders, practical needs).
- Rigour Cycle - connects the research to the knowledge base (theory, prior frameworks, literature).
- Design Cycle - the iterative building and evaluation of the artefact itself.

Hevner et al. defined the DSR as a paradigm with two intertwined goals Firstly, build innovative artefacts (models, methods, frameworks, systems) to solve real-world problems. Secondly, contribute to knowledge in the academic field through the evaluation and refinement of those artefacts [36].

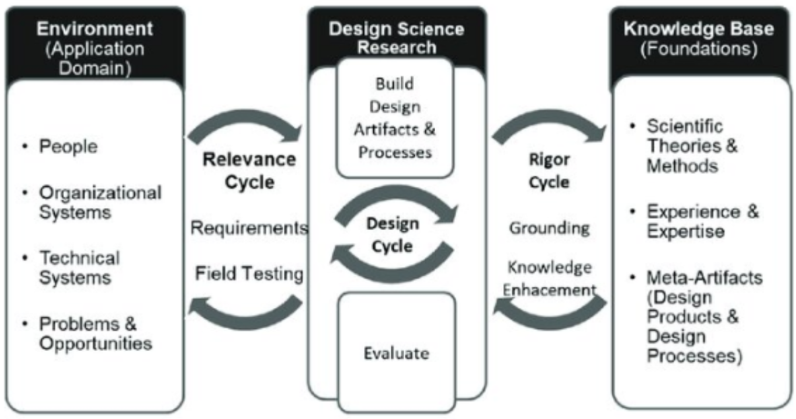


Figure 2.2: Design Science Research Paradigm (Hevner et al.)

Design Science Research emerged as a promising methodology because the construction of the resilience framework follows the characteristics DSR was designed to address: evolving problem definitions, stakeholder learning, and the need for innovative artefacts meant to work in real organisational contexts. The original focus of DSR was designing IT artefacts [46]. For this reason, the method cannot be integrated without modifications to ensure its alignment for this study.

2.3 DSR Application

A widely accepted method of operationalisation of the DSR comes from Peffers et al. According to the article the design research process includes six steps: problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication [56]. Following these steps helps to create the framework and evaluate the work while it is meant to work in a real organisational context.

To make it applicable to this non-IT context, the Design Science Research process is reinforced by the engineering design cycle proposed by Dym et al. with which the steps are divided into phases, providing a structured approach to iterative solution creation [25]. The combination of these approaches ensures both scientific rigour and iterative development of the framework. As a result, the structure is modified slightly compared to the description in Peffers et al. This is mainly because the step "Criteria and Indicator Identification" is added to match the research approach. Additionally, the demonstration step is not considered a separate step, but rather as part of the evaluation.

This is made visible in Table 2.1. To guide the reader, it also shows where the content is addressed. The methodology is described in the following pages of this chapter.

Table 2.1: Design Science Research Phases

Phase	**Description**	**Addressed in:**
1 – Introduction	Problem Identification	1.2
2 – Analysis	Definition	3.1
	Criteria and Indicator Identification	3.2
	Design Requirements	3.4
3 – Design	Design & Development	4.1
	Demonstration	4.4
4 – Evaluation	Validation	5.2
	Communication	6.2

2.3.1 Phase 2: Analysis

To answer the sub-research questions 1, 2 and 3, multiple methods and tools are used. Qualitative approaches assess resilience focusing on depth and meaning rather than statistics. They are particularly useful for identifying the underlying drivers of a problem, its causes, critical areas, and motivations for further development [17]. As discussed in the introduction, a qualitative assessment can serve as an entry point for understanding a situation before progressing to a quantitative analysis. In the energy sector, commonly used qualitative methodologies include in-depth interviews, which are employed to elicit expert knowledge; focus group observations, which provide insights from facilitated discussions among experts; and document review, which involves analysing literature and reports [31]. From this reasoning, these are the methods that will be used for this thesis. Steps that must be included in this process are describing the system and setting the objective [19].

Literature – The study makes use of literature to provide the theoretical foundation for the research. The literature serves two main purposes in this study. First, to establish a clear and academically grounded definition of resilience relevant to the contexts, addressing Sub-question 1. Second, to identify and structure potential criteria and indicators of resilience, supporting Sub-question 2 and 3.

In addition, a brief exploration of Dutch legislation related to critical entity resilience is conducted to examine potential legal or policy implications for companies. This sidestep provides complementary insights into the external factors that may influence resilience assessment and implementation.

Observations – The observations are used as input for sub-questions 1 and 3. The observational data were immediately available and therefore useful for incorporating the industry's point of view into the definition (SQ1). In addition, the data is coded to search for criteria and indicators (SQ3).

Interviews – In this phase interviews are done with direct industry experts and academic experts to gain a clear understanding of how the framework should be designed (SQ2) and what components it should include (SQ3).

2.3.2 Phase 3: Design

The design phase addresses SQ4: How can the criteria be structured into a measurable and multi-criteria resilience framework? In this phase, the theoretical and empirical insights from the analysis stage are translated into a structured, operational framework. The design process follows an exploratory-to-empirical logic: whereas the previous phases identified resilience criteria and indicators, the design phase brings these elements together following the design requirements and develops the conceptual structure of the resilience framework.

The design of the framework builds on the methodological approach used by Yang et al. In line with Yang et al., a multi-criteria analysis (MCA) is operationalised through a hierarchical structure of goal, aspects, criteria, and indicators [72]. This method is adjusted from sustainable forest management by Van Bueren et al. [16]. In such a structure, the overall goal is decomposed into relevant aspects, which are further divided into criteria and associated indicators. This structure provides a reducible approach, while also adopting a theoretical basis for assessing resilience. The decision to utilise this method is a logical consequence of the fact that it provides a highly structured and traceable framework. This is significant as it demonstrates the applicability of the method. The selection and structuring of criteria are adapted to the specific needs of stakeholders, ensuring both conceptual rigour and practical relevance. How this approach is adopted and transformed for the use of this study is outlined in chapter 4.

2.3.3 Phase 4: Evaluation

Due to the time available and timing (December), a concise implementation of this phase is carried out. Meaning the number of respondents is limited. This phase is structured around SQ5, with the purpose of evaluating both the internal consistency and practical applicability of the proposed framework. In addition, it seeks to uncover potential blind spots or misalignments, whether originating from the researcher's interpretation, learning throughout the study or emerging from the perspectives of the interview respondents.

The framework is demonstrated through semi-structured interviews with industry experts, during which participants are asked to look at the framework and reflect on its outputs, the method used to develop and construct the framework and its design. In addition, expertise from OHROS Consulting Group is used in this phase. For this purpose questions like "Would this be a new way of looking at resilience?" and "What do you think of this way of graphing the results?" are asked (more details on the interview are in Appendix C). This helps to secure market alignment and empirical validation [25].

2.4 Overview of methods

This section provides an overview of the methods used to gather and process data. This study is mainly based on qualitative methods. The study combines literature, observations, and semi-structured interviews. Source triangulation is used to enhance the external validity of the study. This is done to integrate literature analysis, data analysis and primary stakeholder interviews [34].

2.4.1 Literature

Data collection - The focus of this study is not on conducting an extensive literature review. The review of literature provides the basis for understanding the current state and future development. Therefore, a flexible rather than strictly systematic approach is adopted to capture the full scope of relevant developments. This means the review is not fully according to the PRISMA guidelines [49]. However, the steps from the guideline are used to provide structure. These steps are identification, screening, eligibility, and inclusion.

Due to the significant increase in publications in recent years, backward snowballing is mostly applied. This made it easier to find good and relevant information. Literature was searched using the following search terms using Boolean operators:

- Resilience
- Defining resilience AND technology
- Asset management AND resilience
- Critical infrastructure AND resilience
- Energy systems AND resilience
- Resilience framework

- Resilience assessment framework
- Resilience assessment AND critical infrastructure

“Cyber”-related research is excluded from the search because it brought up studies that were too specific. This is done with AND NOT “cyber”. This search is done in multiple databases: Science Direct, Research Gate, EU database, institutions and via search engines such as Google.

The decision to search for the term "infrastructure" as opposed to "entities" is predicated on the observation that the former is utilised with greater frequency. In the initial search for entities, the number of relevant results was found to be almost non-existent.

Data processing - The literature data are processed using Microsoft Excel. Following the literature search, relevant publications are systematically recorded and organised in a structured spreadsheet. Key information, including authorship, title, year of publication, research focus, and identified resilience-related concepts, criteria, or indicators, is extracted and coded this is elaborated in section 4.2.

2.4.2 Observations

Data collection – International Transmission Asset Management Study (ITAMS) is a learning collaborative that shares knowledge and best practices. Twelve participants from the energy transmission sector[1], operating globally and managing grids with an average length of 40,000 km, took part in the most recent cycle 2024–2025 (see appendix B for more information about the participants). As a host of ITAMS, OHROS Consulting Group provides access to all available data and information, including qualitative and quantitative data, best-practice interviews, and work group webinars. This also includes recordings and materials from the conference concluding the most recent cycle, held in October 2025.

This source is treated as observational data, capturing sector-wide perspectives and discussions among experts. The topics covered are Digitalisation, Grid of the Future, and Resilience, where resilience is the main input for this study. Reflecting on current strategic challenges and priorities within the energy transmission industry. Insights from these observations are used to contextualise relicense and identity criteria and indicators.

Data processing: The insights are analysed using a coding strategy, which is explained in more detail in section 3.2. This analysis is conducted in Microsoft Excel, as it is the same tool used for the literature analysis and is user-friendly.

[1] Transmission System Operators (TSO) operate under mutual market forces and are therefore not in competition with each other. Emphasising the value of the knowledge they share, as it is not driven by commercial purposes.

2.4.3 Semi-structured Interviews

Participant selection - Given the scope of the field and the time constraints of this study, a purposive selection of participants is applied. Participants are drawn from the strategic organisational level, as these perspectives are essential for developing a well-informed understanding of resilience within the energy sector, and are the ones who apply it in their daily work. The recruitment of experts is done considering qualification criteria to guarantee relevant expertise:

- Minimum 10 years in the industry
- Active involvement with resilience or asset management
- Responsibilities or active in a critical entity (energy)

Only a limited number of participants can be recruited for the interviews conducted during the evaluation phase. The recruitment of experts follows the same approach. However to ensure a balance and fair evaluation, an additional participant with specific expertise in the field of resilience, who was not involved in the initial interviews, is also approached. The recruited experts are outlined in Section 3.2 and appendix C.

Interview data collection – All interviews are held one-on-one via Microsoft Teams. Semi-structured interviews are the preferred method as they are adept at eliciting in-depth and context-rich insights into respondents' interpretations and operationalisations of abstract or complex ideas [3]. This methodological approach facilitates the exploration of not only the stated definitions but also the underlying assumptions and frames of reference that shape respondents' understanding [74]. Complete protocol specification is attached in appendix C.

The interviews are recorded and transcribed using PLAUD.ai, which is made available by OHROS. The data is processed according to the TU Delft Human Research Ethics Committee (HREC) guidelines for the protection of participant anonymity and secure data handling.

Data processing – The anonymised data is coded with ATLAS.ti (2025). A structured analysis is conducted, following a code strategy that is explained in more detail in section 3.2.

2.5 Research Flow Diagram

Because this study employs DSR and draws on real-world experiences from various companies worldwide, it contributes to both scientific and practical understanding. In Figure 2.3 on the next page, a visual representation of the research is shown. This visualises how the research techniques contribute to answering the sub-questions.

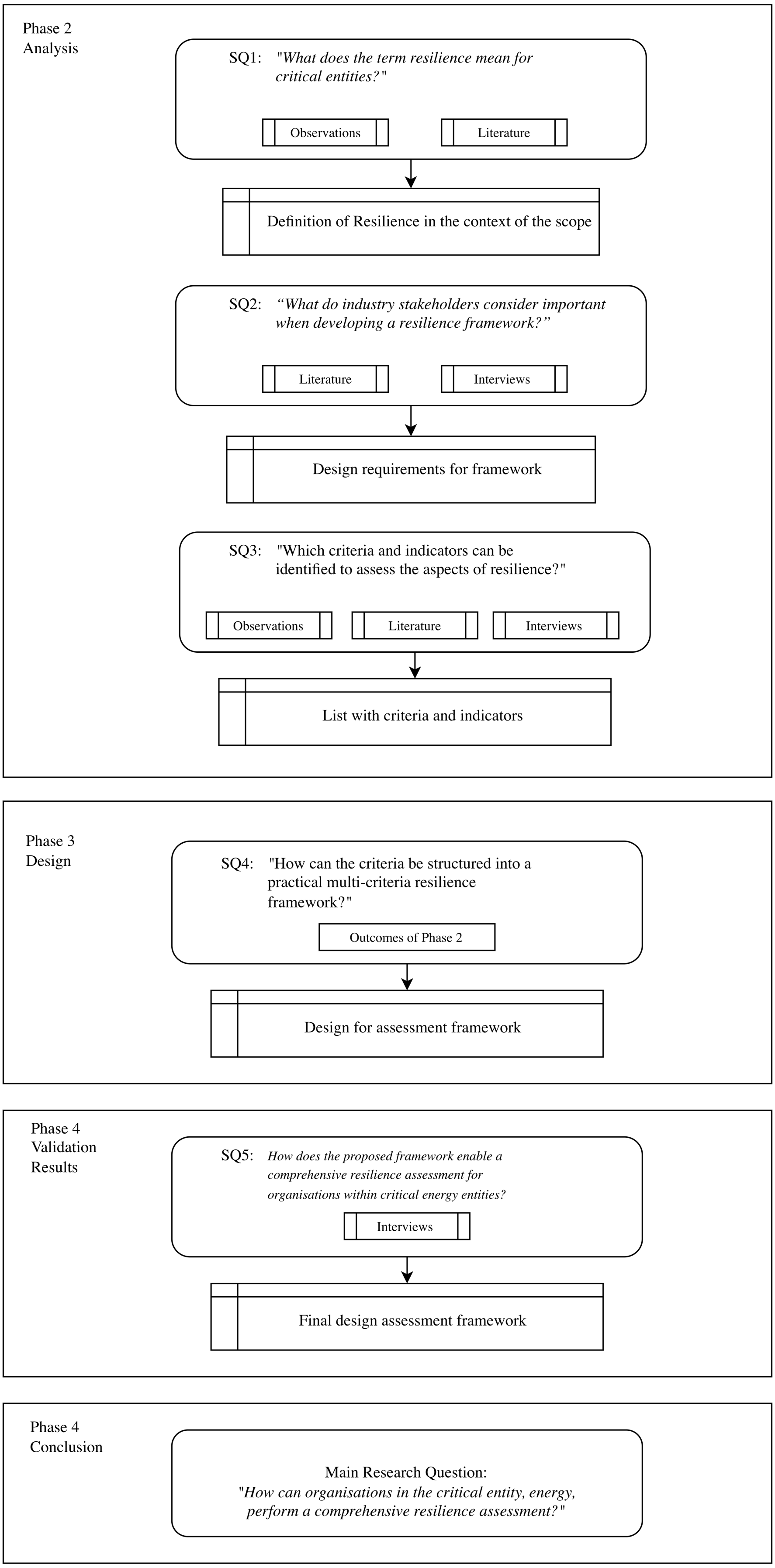


Figure 2.3: Flowchart research design

3

Analysis

This chapter elaborates on the definition of resilience for the sector. The analysis and identification of criteria and indicators are conducted after the data are collected. This process also involves examining upcoming changes in Dutch legislation and regulations. Finally, the design requirements are formulated at the end of the chapter.

3.1 Defining Resilience

There is still no global consensus regarding the definition of resilience. It is a concept that is hard to operationalise, which makes it difficult to have a universal definition across the academic, political, and industry landscapes. It changes according to the socio-technical-environmental system. Carpenter et al. points out that one must consider resilience of what and resilience to what [18]. These questions shift the focus from general resilience, the capacity to deal with the unknown, to specified resilience. However, this still does not provide a clear definition of what resilience is. The following section will address the questions of resilience *of What* and *to What*, and comes with a definition of resilience for this scope, *is What*.

3.1.1 Resilience of What

The critical entity energy relates to energy organisations and systems that are characterised as critical to society's functioning. Critical entity derives from the EU Critical Entities Resilience (CER Directive (EU 2022/2557) [27]. Critical Entity is the replacement of the term Critical Infrastructure and includes 11 critical sectors that are identified as essential for maintaining vital societal functions [26]. As mentioned in the introduction is the energy sector an asset-intensive industry. Asset-intensive industries are sectors that rely on significant capital for expensive, high-value physical assets. This is also why the concept is closely related to asset management, where the objective is to get value out of assets by balancing cost, performance and risk.

The energy sector is essentially the system that produces, transports, and delivers energy (mainly electricity, gas, and oil) to consumers. It includes several layers such as generation, transmission, distribution, and supply. Generation has the role of generating power and feeding electricity into the transmission grid. This is a competitive market (e.g Vattenfall, Eneco, and Shell Energy). Transmission System

Operators (TSOs) operate and maintain the high-voltage grid and ensure balance between supply and demand. TSOs are not competitive most of the time there is one company (e.g. TenneT in the Netherlands). Distribution System Operators (DSOs) operate the medium and low voltage networks and deliver electricity from the transmission to households and local infrastructure (e.g. Stedin, Liander, and Enexis). Supply sells the energy to consumers but doesn't own infrastructure and therefore is not designated as critical.

Taken together, the energy sector and its asset-intensive nature underscore the importance of a structured approach to managing disruptions, low probability high impact and long-term risks. The strong dependence on long-lived, high-value assets, combined with the sector's essential societal function, means that failures can have far-reaching consequences beyond the organisations directly involved.

3.1.2 Resilience to What

The To What question relates to root-cause analysis, such as the 5 Whys method and helps create understanding of the challenges. But as highlighted already, it is also about preparing for the unknown (Black Swan) [4].

Mitchell et al. describe that there is a distinction between shock and stress. Shocks can be only temporary or have an irreversible effect on the function. Long-term stresses develop as a gradual change of the system's environment. It is important to recognise the differences because it may require different measures to be taken [48], especially when programming for enhancement planning techniques. When programming is used, the simulation and reality diverge considerably if considered a shock rather than long-term stress. Examples of known challenges are included in Figure 3.1.

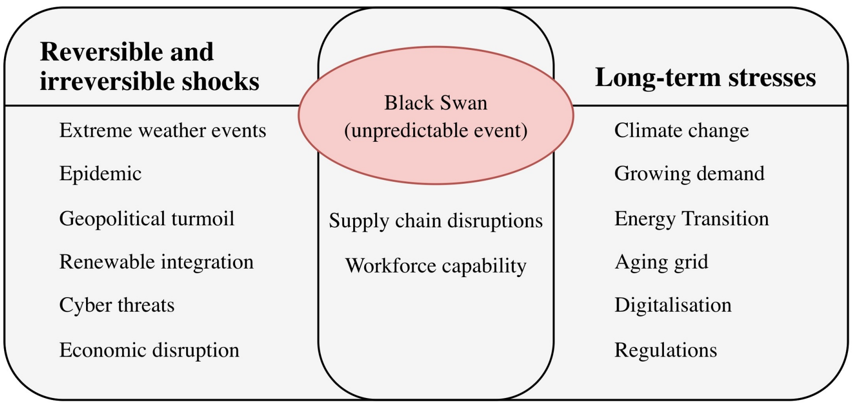


Figure 3.1: Examples of challenges affecting energy systems, subdivided into shocks and long-term stresses

Within the industry, the To What question is being utilised more often, as it offers a method for problem-solving. This also came back in one of the interviews and is interesting to mention here. As Respondent 3 noted, there are always new challenges coming up every day. Observations revealed that participants primarily considered extreme weather events (e.g. high winds, floods, lightning) and cybersecurity. An example for this is a tool shared by a respondent, which identifies four focus points: cyber, physical security (sites & cables), vegetation, and climate. This aspect was previously characterised by the respondent as predominantly technical, given that many of the identified resilience measures are technically related. These mechanisms facilitate the determination of relevant factors, thereby enabling the focus to be ascertained.

Overall, the To What question supports organisations in structuring their understanding of vulnerabilities by distinguishing between immediate shocks and long-term stresses, and by identifying their underlying causes. It guides to strengthen preparedness for uncertain and emerging threats.

3.1.3 Resilience is What

Despite the extensive body of literature, the definition of resilience remains fragmented. Existing interpretations often overlap in their core ideas but diverge in emphasis, scope, and application. This conceptual ambiguity has been repeatedly highlighted in recent reviews, such as the systematic literature review on resilience assessment in critical infrastructures (2014–2024) by Marco et al. (2025) and the comprehensive review of resilience definitions and frameworks by Babu et al. (2025). Both studies emphasise the ongoing lack of a shared understanding of resilience across disciplines and sectors [47, 11].

As one of the earliest contributors, Holling (1973) provided a foundational definition of resilience as “the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.” This ecological perspective introduced the idea of resilience as a system’s capacity to endure and recover from disturbances without losing its core functionality [37].

In 2002, Holling et al. described resilience theory as emphasising change, uncertainty, and the capacity of systems to adapt, and introduced the concept of adaptive cycles. The concept of adaptive cycles originates in ecological systems thinking, where they represent different stages (growth, conservation, collapse, reorganisation) through which systems might pass in response to changing environments and internal dynamics [38]. After Holling’s contribution, the ecological literature distinguished two types of resilience: first, "ecological resilience," which is the ability of systems to absorb change and persist after an external shock, and second, "engineering resilience," which deals with resistance to disruption and the speed with which systems return to pre-existing equilibrium [6].

Building on this, Bruneau et al. (2003) made a significant contribution by translating the concept into the engineering domain. They identified four key properties of resilience: robustness, redundancy, resourcefulness, and rapidity, now also known as

Framework proposed by Adams et al.				
	4Rs			
Robustness	+	Redundancy	=	Reduction
Resourcefulness	+	Rapidity	=	Recovery

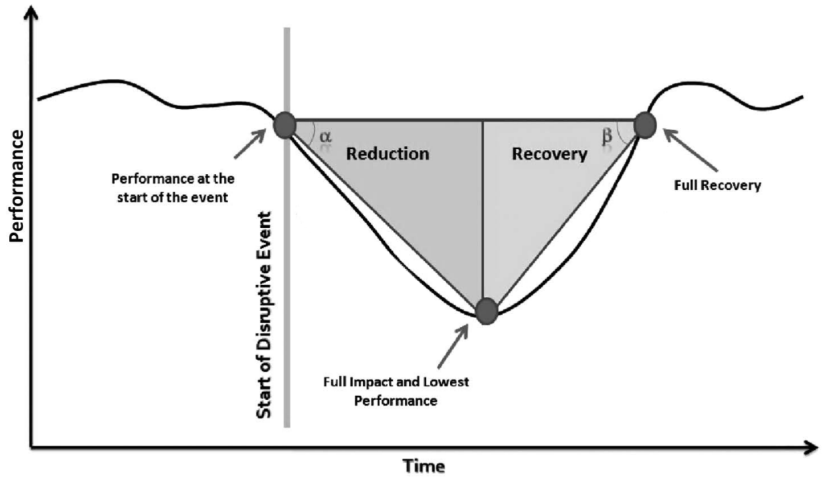


Figure 3.2: Resilience triangle (Adams et al.)

the "4Rs" (see Appendix D for more detail on explanation). Building upon the 4Rs framework, Adams et al. proposed two measures of resilience: reduction and recovery (see Figure 3.2). Reduction (α) is defined as the combined ability to withstand disaster forces without significant loss of performance and the ability to substitute other system elements. Recovery (β) combines the measures that act to restore system function, resourcefulness, and rapidity [2].
In addition to the four properties (4Rs), the four interrelated TOSE dimensions are introduced by Bruneau et al.:
technical, the ability of systems to maintain functionality under stress;
organisational, the capacity of institutions to decide and act effectively during disruptions;
social, measures that reduce impacts on communities;
economic, the ability to limit and recover from financial losses.
This model proposes a multifaceted classification that considers both external (technical) factors and internal (organisational) factors, offering a comprehensive framework that integrates physical and socio-economic perspectives [15].

Some definitions specifically apply to be for the electric sector. In the context of the electricity grid, for example, Panteli et al. (2016) define resilience as “the ability of the system to withstand high-impact, low-probability events, recover quickly from such events, and adapt its operation and configuration to mitigate potential future events” [54]. Another example of this is the electricity grid resilience by the Institute of Electrical and Electronics Engineers (IEEE) Task Force given in Table 3.1 together with five other resilience definitions.

Table 3.1: Resilience definitions in the most recognised papers

Definition	Author:	Year
the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables	Holling	1973
the capacity to adapt or transform in the face of change	Folke et al.	2002
the ability of social units (e.g., organisations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimise social disruption and mitigate the effects of future disasters	Bruneau et al.	2003
the ability of a community to prepare and plan for, absorb, recover from, and more successfully adapt to actual or potential adverse events in a timely and efficient manner	Cutters et al.	2014
an overarching concept that encompasses the system performance before and after disastrous events	Zhaohong et al. (IEEE)	2017
the capacity to restrict both the magnitude and duration of system degradation, thereby ensuring the continued provision of essential services following a catastrophic event.	Stankovic et al. (IEEE)	2023

Reliability and resilience are different perspectives on the same underlying problem, but they are often confused with each other. Improving reliability is an outcome of resilience-oriented solutions. Some key resilience characteristics that differentiate it from the concept of reliability are shown in Table 3.2. Another common misconception is the distinction between risk and resilience assessment and management. Risk assessment considers a pre-event analysis to provide a characterisation of the potential risk of disruptive events. This usually results in preventive measures to minimise the frequency and consequences of disruptions. In contrast, resilience assessment includes not only the analysis of potential disruptive events but also post-event analysis [31].

Table 3.2: Reliability versus resilience

Reliability	Resilience
High probability, low impact	Low probability, high impact
Ability to repeatedly perform its intended task successfully	Ability to sustain a failure and continue performing its duties
Static - Consistency of performance under normal conditions	Adaptive - Adaptation and recovery under abnormal conditions or failures
Concerned with customer interruption time	Concerned with customer interruption time and the infrastructure recovery time
Reliability depends on resilience; without resilience, failures will eventually reduce reliability	Resilience enables reliability by ensuring the system survives and adapts to failures

These insights contribute to formulating the definition of resilience for the energy sector in this scope. Rather than striving for a single universal definition, it may

be more meaningful to focus on the broader concept of resilience by highlighting its key properties and dimensions. A systems-oriented definition is offered by the Designing Systems for Informed Resilience Engineering (DeSIRE) programme, an interdisciplinary research initiative. DeSIRE defines resilience as "the ability of a socio-technical-environmental system to sustain, improve, and innovate its key functions—through absorbing, reacting to, recovering from, adapting to, or reorganising—in response to chronic stresses, abrupt shocks, and disruptions" [39].
When combining this definition with the notion that resilience is characterised and graphed by the two measures of resilience proposed by Adams et al., the concepts provide a comprehensive understanding.

3.2 Criteria identification

As elaborated in Section 2.3.1, multiple methods are used to identify criteria for assessing resilience. This mixed-method approach is beneficial, particularly given the emerging need for knowledge triangulation. All methods are analysed using a coding approach to provide a theoretical ground. During this coding process, there has been a back-and-forth movement between the data as new identifiers were identified.

3.2.1 Criteria from the Literature

The focus of this study is not on conducting an extensive literature review. The literature is searched as outlined in Section 2.4. Based on the literature, a rough distinction can be made between bottom-up and top-down approaches to developing indicators. Top-down approaches begin with a theoretical framework that serves as the basis for selecting relevant variables. In contrast, bottom-up approaches typically arise from dissatisfaction with the limited attention given to local-scale factors. Although they are labelled 'bottom-up', such approaches are in practice most often mixed-methods, combining more general (top-down) indicators of resilience and vulnerability with place-specific (bottom-up) resilience factors [23]. In this case, a mixed approach is used.

In their review of qualitative research approaches within the context of critical infrastructure resilience, Cantelmi et al. establish that interviews are the most commonly used method [17]. In addition to demonstrating the effectiveness of interviews as a research method, the paper also provides extensive input on the list of criteria and indicators, drawing on its comprehensive analysis of 98 studies (e.g. effective partnership, decision-making abilities, information-sharing). Literature such as Sapeciay et al. provides valuable insights on indicators for resilience, although it is applied to another industry. They identified 16 potential resilience indicators for construction organisations (e.g. leadership, planning strategies, internal resources) [61]. In total a number of 76 studies were screened in this search. Providing over 150 potential indicators.

3.2.2 Criteria from the Observations

Based on the knowledge gained from the literature search, the available data provided by OHROS Consulting Group were analysed. As mentioned earlier, these data consist of observations from a learning collaborative involving twelve participants from the energy transmission sector, see Appendix B for more details. The observations include keynote speeches, panel discussions, and workshops with and from industry experts.

In the first phase of the analysis, open coding following the approach of Strauss et al. [67] is used. This exploration phase aimed to remain as close as possible to the data and therefore applied an inductive coding strategy, allowing concepts to emerge directly from the data rather than imposing predefined categories. Sensitising concepts in the sense described by Blumer [13] was used as broad, flexible points of orientation. This means concepts did not function as strict analytical categories but instead helped guide attention toward relevant phenomena while still allowing room for unexpected insights to emerge. Following the open coding process, a list of 69 potential codes (indicators) was obtained.

3.2.3 Criteria from the Interviews

For this research, six respondents were interviewed, consisting of two academic experts and four industry professionals. All have experience in resilience or asset management strategies. The participants represented different regions across the world, providing a more global understanding of the topic, and came from various layers of the energy sector, ensuring that multiple organisational perspectives were captured. The interviews were held around November 2025. An overview of the respondents is presented in Table 3.3

Table 3.3: List of respondents in interview

Respondent	**Role:**	**Experience (years)**
Respondent 1	Academic	
Respondent 2	Academic	
Respondent 3	Manager - Strategic Asset Management	15+
Respondent 4	Director of Asset Management	15+
Respondent 5	Risk Manager Digital Security OT	12
Respondent 6	Director of Asset Management	15+

The interviews were conducted in a semi-structured format to explore the respondents' views on resilience, clarify ambiguous concepts, and validate the preliminary list of criteria and indicators explored from the literature and observations. The interview protocol used for this purpose is provided in Appendix C. During the interviews, the preliminary criteria were discussed to assess their relevance, clarity, and completeness, and to identify any additional criteria that had not been previously identified in the literature and observations. The interview data were analysed using the same open coding approach applied to the observational data. Through inductive open coding, new and sensitising concepts were identified. This allowed for a deeper understanding of how the industry stakeholders perceive resilience. This resulted in a list of 166 potential indicators. At this stage, no comparison was made with previously established codes. Consequently, the list may contain overlaps and duplicates. The indicators therefore do not represent novel constructs, but rather an initial, unrefined collection that will be systematically consolidated, refined, and reduced in the next coding phase through combination, modification, and deletion.

Empirical Findings from Interviews

What has become clear from the interviews is that the organisations identify most indicators based on standard risk analyses or lessons learned after a disaster/blackout (R3). Their approach to resilience is mainly based on their own experiences and varies greatly from one organisation to another. This is in line with what Academic R2 indicates, in particular that organisations should sketch scenarios, identify risks, and "attach criteria" to those problems.

In addition to the identification of indices, the interviews also provided several insights of particular significance. Among these insights were the following:
Introducing the concept of resilience and the division into four aspects helped respondents articulate their understanding. Many interviewees mentioned that the introduction of resilience and the division into aspects provided immediate clarification and allowed them to think about resilience from an organisational perspective rather than only technical (R4, R5, R6). It should be noted that many components are included in operations, yet they are not regarded as part of resilience. Responded 4 states that it would be a huge benefit to probably every industry, to look this way, each of these areas is a focus on an actual outcome.

A recurring theme across the interviews was the belief that a resilience framework would support practice by making the concept more concrete, structured, and applicable. Respondents explained that a framework would primarily improve situational awareness, helping organisations gain a clearer understanding of their current resilience (R1). In addition, respondent 3 noted that such a framework would enable maturity assessment, allowing organisations to evaluate how their resilience develops over time and to track progress in a systematic way. It was also highlighted that a framework could introduce resilience metrics, which would support more informed decision-making by making resilience measurable rather than abstract (R4). A further motivation was the framework's potential to reveal blind spots—aspects of resilience that organisations may overlook when assessments remain informal or fragmented (R6). At the same time, participants were critical of existing resilience frameworks, which they described as "not very operationalised" and "quite vague," leading to outputs that "are not really concrete" (R1). As R2 noted, a usable framework must be "broadly applicable, but not so vague that it becomes meaningless or overly subjective."

Furthermore, organisations use N-1 design, duplicating critical components so the system continues to operate even when one part fails, as continuity must be guaranteed (R5, R6). "So that's very robust, and therefore also very resilient", but that is a common mistake. Some measures might make the system more resilient operationally but less resilient from a maintenance perspective. For instance, relocating an overhead corridor underground may enhance the system's ability to withstand events however if the cable is damaged, it may take significantly longer to repair it than an overhead line [53].

Building a bigger and stronger (more redundant and robust) network is not a sustainable, cost-efficient approach. Consequently, some companies are also examining the capabilities of resilience. Capabilities take another point of view on resilience. Capabilities include preparedness, response, recovery (e.g emergency plans, repair crew available) [12]. R3 explained that their organisation already works with a structured five-step strategy, consisting of: prevention (the preferred option, although not always possible), preparation (ensuring readiness), detection (identifying disruptions as early as possible), response (acting according to trialled and tested plans), and recovery (returning to normal operations as quickly as possible), also know as response stages. As a result, they have comprehensive contingency and crisis management plans in place. These plans are not merely documented but are actively practised and tested in real exercises, a point also emphasised by R5. This is the opposite of what R6 refers to when it comes to resilience. "Our thinking is really very much focused on prevention. We are assuming business as usual and basing our scenarios on that, and they are not that wild in the sense that they take very extreme things into account, e.g. war." It really is extrapolating from an existing line. Interviews reveal that if you look at it this way, you can identify what is important at each stage. For example, transport is an issue during an acute disaster (flooding). "Even if contingency plans are in place or there is a crisis management plan, during a disruption, you are often not the only one who needs something, so you have to make agreements or decide how this will be arranged" (R3). What emerges here is something that has also been noted in the literature search. Namely, that you can also take an alternative approach to resilience that divides it into separate phases. This raises the question: resilience at what stage? (Planning Preparation, Absorption, Recovery, Adaptation [35, 59, 73]. However, this has not been included because it can be argued that actions in, for example, the recovery phase must also be determined and planned. Consequently, it can also be disregarded as an indicator.

Moreover, it became clear among the respondents that there is a desire to quantify resilience. Several participants emphasised that without some form of measurable assessment, resilience remains too abstract to guide decision-making or organisational improvement. As R4 explained, even a simple scoring approach “a red–amber–green status" for each of these, would already create clarity and make progress (or lack thereof) visible. Similarly, R6 highlighted that quantification helps organisations reflect on their actual performance, like a Capability Maturity Model Integration (CMMI), this way shows what we are actually doing about it, whether we are doing enough, and whether we are giving it the attention it deserves. Something to take into account in the requirements.

In addition, respondents identified internal and inter-organisational challenges that shape their ability to improve resilience. "I would add that we are actually the opposite of a start-up. We have been around for so long, and we have a business that is so focused on continuity. This means that we are very resistant to change" (R6). In addition, the time horizon being considered ranges from 10 to 80 years ahead (R4, R5, R6). For long-term planning, it is still difficult to figure out if and how to integrate resilience into plans (R1).

Interestingly, the prioritisation of the economic aspect of resilience was generally not perceived as highly important by the respondents. Several interviewees explained that financial considerations are, in practice, often separated from their core responsibilities. As R4 noted, “the cost of it isn’t my problem”. Similarly, R6 explained that operational costs are typically covered, yet acknowledged that unexpected events, “something that is out of our scenarios,” could still put the organisation in a vulnerable position. R5 added that although routine costs are accounted for, additional resilience-enhancing measures, such as improving site security, often fall outside available budgets. While R3 recognised that costs “are always important,” they were nonetheless described as not a priority compared to other resilience dimensions.

Finally, an underlying issue raised by the respondents concerns the challenge of building trust between different parties. As R1 explained, there must be a shared understanding that exchanging data and knowledge serves the collective interest and ultimately helps all organisations strengthen their resilience. Without this trust, collaboration remains limited and opportunities for sector-wide improvement are constrained.

3.3 Dutch legislation

As previously mentioned, a concise analysis is provided concerning legislation and regulations. From the CER Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 the Dutch act "Wet weerbaarheid kritieke entiteiten" was derived. The Act requires critical entities to conduct their own risk assessment concerning all relevant threats that could disrupt their services. The aim is to identify potential threats, vulnerabilities and hazards that could lead to an incident and to assess the extent of the impact. The act describes three key elements: Risk assessment (Risicobeoordeling), Duty of care (Zorgplicht), Duty to report (Meldplicht) [71].

Risk assessment - allows the resilience level of a critical entity to be determined, and in doing so, helps identify potential actions for improvement. Critical entities should document and apply these insights, with a cycle of a maximum of four years.

Duty of care - refers to the obligation of the CEs to take appropriate and proportionate technical, security and organisational measures to ensure their resilience. This is in line with what is already seen. What is interesting to emphasise here is that the law also makes use of resilience in the form of before and after disruptions, as mentioned in several interviews. The subsequent measures noted in the context are:

- Prevent incidents from occurring.
- Ensure adequate physical protection of buildings and critical infrastructure.
- Combat the consequences of incidents.
- Recover from incidents.
- Ensure the organisation of personnel security.
- Make the relevant personnel aware of the aforementioned measures.

The Duty to report - implies the obligation to report incidents that significantly disrupt or could disrupt the provision of their essential service to the competent authority.

The act was prepared on 4 June 2025. However, despite the EU deadline having passed, the act has not yet been passed. The latest Nota of 4 November states that political parties emphasise the importance of a high degree of independence and standardisation in the way risk assessments are carried out. However, this matter has not yet been concluded. This can also be regarded as the most significant vulnerability. It is incumbent upon the company to undertake a risk assessment and thereafter determine the focus and scope. Aligning completely with the gap identified and mentioned earlier. It is therefore not surprising that, based on the interviews with the Dutch participants, no (new) measures were taken in response to the Act. Nonetheless, it is recognised that increased attention may be required for several matters (e.g., site security, personal awareness).

3.4 Design Requirements

The requirements underlying the framework can be grouped into three complementary categories. Functional requirements describe what the tool must accomplish to address the challenges identified in the analysis phase; they capture the essential capabilities the framework should offer. Structural requirements specify how the tool should be constructed and which components or internal architecture it must contain in order to operate effectively. Finally, contextual requirements reflect what intended users need from the tool in their day-to-day practice, ensuring that the framework aligns with organisational processes, decision-making realities, and practical constraints [41].

Functional requirements:
A core functional requirement is that the framework must establish a clear, shared, and context-specific definition of resilience. Multiple respondents stressed that resilience is not yet a familiar or consistently understood concept within organisations. As R6 articulated, without a common definition, “people will come to the table with their own ideas... and talk past each other”. The framework must therefore operationalise resilience in a way that aligns perspectives and prevents misinterpretation.

Several respondents (R1, R2, R4) highlighted that the framework should support an integrated view of resilience. While some organisations may be strong in specific TOSE dimensions (typically the technical domain), they often overlook social, organisational, or economic. As R4 noted, most organisations in the sector “are incredibly strong on the technical areas... but all the things you brought out make sense to me from an overall business perspective”. Thus, the framework must function as a tool that exposes blind spots, encourages cross-dimensional reflection, and strengthens situational awareness beyond technical capabilities alone (R2). R6 explicitly expressed the need to recognise where organisations “are not yet very familiar” or may have implicit assumptions.
A final functional requirement is that resilience should not be approached as a static characteristic but as a continuous organisational process. Respondent R1 emphasised that resilience “should be seen as a process”, and the framework should function accordingly. This means that the tool must guide users through identifying, monitoring, and revisiting resilience factors over time. Functionally, the framework must enable iterative assessment and reflection, rather than a one-time evaluation.

Structural requirements:
Contrary to expectations, there were fewer specific structural requirements for the framework than anticipated. Respondents either did not provide any suggestions or showed their own tools and frameworks. It appears that many respondents do not necessarily indicate what they want to see, but rather how they want to use it. As with R6, who indicates that, upon establishing resilience, they wish to proceed further, the manager’s role entails a desire for a comprehensive understanding of the organisation’s activities. Nevertheless, several structural expectations emerged that guide the development of the resilience framework.
Respondents emphasised that the framework must be easy to navigate and accessible to different types of users. R2 specifically noted that, in order to be applicable across various organisational contexts, the framework must remain readable and straightforward. This implies a structure that avoids unnecessary complexity and communicates clearly across all TOSE dimensions. A readable structure increases usability and helps ensure adoption in practice.
R2 also stressed that the framework should not strive for a “perfect fit” for every organisation or situation. Instead, it should be designed in a modular way, allowing users to skip components that do not apply to their context. This flexibility supports broad applicability without compromising clarity.
A recurring theme was that managers want structural clarity that supports an overview of organisational activities. For example, R6 indicated that once resilience is defined and assessed, they want to “proceed further” by understanding how different elements of the organisation fit together. This implies that the framework must be structured in a way that provides both detailed insights and a high-level overview. The structure should therefore support both granular analysis and managerial interpretation.

Contextual requirements:
As R1 emphasised, there is a need for "more longitudinal data to examine the current situation and have a way of adopting or observing these changes along the way". Therefore, the framework must be applicable across different points in time
To make the framework practical and comparable, R5 argued that a maturity model such as the Capability Maturity Model Integration (CMMI) is needed. A maturity structure provides organisations with insight into how developed their resilience capabilities are, and it enables benchmarking across departments, time periods, or even across organisations.
Finally, the framework must fit within existing organisational routines and decision-making processes. For users, resilience assessment should not become an isolated or additional administrative burden. Instead, it should integrate naturally with planning cycles, risk assessments, audits, and managerial reviews. This contextual requirement ensures that the framework is not only theoretically robust but also feasible and sustainable in practice.

These requirements can be summarised as shown in Figure 3.3. The literature and interview data indicate a consistent alignment among respondents, as no contradictory perspectives on the requirements were identified.

Functional Requirements

- **DR1** – Shared Definition
- **DR2** – Integrated TOSE Perspective
- **DR3** – Process-Oriented and iterative Assessment

Structural Requirements

- **DR4** – Readable & Accessible Structure
- **DR5** – Modular Design
- **DR6** – Overview and Detail Support

Contextual Requirements

- **DR7** – Longitudinal Applicability
- **DR8** – Maturity-Based Evaluation
- **DR9** – Integration with Organisational Routines

Figure 3.3: Summary of the Design Requirements

4

Design of the Framework

With the design requirements established, this chapter focuses on the conceptualisation and structuring of resilience. It outlines how the methodological approach described in Section 2.4 is used for the design of the framework. The open coding criteria identified in section 3.2 are selected and further developed according to a coding strategy. This is used to develop the framework.

4.1 Designing

The design of the framework builds on the methodological approach used by Yang et al. In line with Yang et al., a multi-criteria analysis (MCA) approach is operationalised through a hierarchical structure of goal, aspects, criteria, and indicators [72]. This method is adjusted from sustainable forest management by Van Bueren & Blom [16]. In such a structure, the overall goal is decomposed into relevant aspects, which are further divided into criteria and associated indicators as illustrated in Figure 4.1. This structure provides a reducible approach, while also providing a systematic basis for assessing resilience. The decision to utilise this method is a logical consequence of the fact that it provides a highly structured and traceable framework. This is significant as it demonstrates the applicability of the method. The selection and structuring of criteria are adapted to the specific needs of stakeholders, ensuring both conceptual rigour and practical relevance.

To adapt the approach to this study's context, three steps were taken. First, a guiding framework was selected: the TOSE dimensions (Technical, Organisational, Social, Environmental) from Bruneau et al., which provide a broad theoretical foundation for categorising resilience. This formed the second layer of the framework, establishing the aspects. Second, the theoretical and empirical indicators derived from the analysis phase are mapped onto the TOSE structure, allowing empirical insights to refine, adjust, or extend the theoretical categories. Third, criteria are created, ensuring that the resulting set of criteria is concise, coherent, non-redundant, and suitable for measurement. Based on these steps, a conceptual and detailed solution is developed, resulting in a set of criteria and indicators that form the resilience framework.

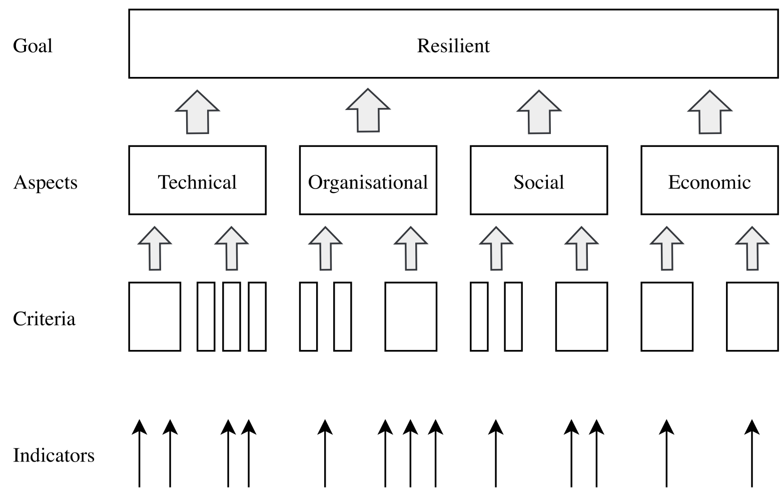


Figure 4.1: Hierarchical structure with TOSE, adjusted, sources: [16, 72]

4.2 Selection of Criteria and Indicators

In order to provide a theoretical foundation, the second phase of coding was applied in ATLAS.ti (2025) for the interview data and MS Excel for the literature and observation data. The second phase of coding continues on the first phase.

The first phase followed an open coding process. The second phase of coding would be axial coding if an inductive approach were strictly followed [67]. But because of the methodological approach and the adoption of the TOSE dimensions it felt logical to divide the open codes into the TOSE first. Resulting in an abductive approach in which inductive and deductive reasoning are combined. Inductive reasoning moves from observations or data toward theory, whereas deductive reasoning follows a top-down approach from theory to practice. Abductive research begins with an incomplete set of observations and seeks the most plausible explanation. Rather than aiming to produce generalisable conclusions, it focuses on developing a theoretical interpretation that best fits the empirical data. Abductive analysis is particularly valuable in situations where no clear or linear pathway exists between data and theory [42], and therefore a suitable method.

So the first step was to allocate the open codes to the selective TOSEs. Not all indicators can be strictly categorised into a single aspect. Some examples of this are logistics, innovation, and data sharing. These have been placed in multiple aspects, which will be processed in the next phase. This also illustrates why it is preferable to move from open codes to selective codes before applying axial coding. For example, data sharing has both a technical and a social dimension, as emerged from the interviews. From a technical perspective, it must be arranged and enabled, while from a social perspective, it must be structured for both internal and external sharing to improve joint insights and response speed.

After the selective coding, axial coding is applied. In this step the codes are refined, and dubbing is reduced. The codes from ATLAS.ti have been combined with the codes in MC Excel. Due to the large volume of data, it was difficult to maintain an overall overview. Therefore, after the selective coding phase, post-it notes were used to make the process more manageable and to enhance clarity. This made it easier to identify connections and establish criteria. The pre-axial coding and post-exaeil coding snapshots are shown in Figure 4.2. The indicators are grouped into criteria. For example, *cyber security* (T1.1), *asset security* (T1.2) and *physical security* (T1.3) are grouped under the criteria *security* (T1). The three data sources have collectively yielded a list comprising 19 criteria and 89 indicators. For details, see the Appendix E, which includes a list with numbering, description and reference.

Figure 4.2: Visual snapshot of the coding process, illustrating the development from selective coding to axial coding

To provide insight into how this process unfolded, let's continue with the example of data sharing. This is reflected in technical terms as *data transparency and sharing* (T3.5) and in social terms as *data sharing* (S4.2). This example also illustrates the interconnections between data sharing and other factors, such as data quality, standardisation, long-term relationships, and, consequently, trust.

Another example of how the coding steps were carried out is the category *People and Competence* (O2). The associated open codes include: equipped to do the job, workforce capability, engaged workforce, technical competency of people, learning, skills and capacity. These were subsequently consolidated into the indicators *Community* (O2.1), *Skills and abilities* (O2.2), *Learning* (O2.3), and *Workforce en-*

gagement (O2.5). In addition, *Motivate people* (O2.4) was included, although it did not explicitly emerge from the data. This indicator was added based on prior theoretical knowledge and supporting literature, which identifies motivation as a critical component of organisational resilience. Notably, a correlation exists between these indicators. The development of skills and abilities is facilitated by the application of learning principles.

Figure 4.3 provides a visualisation of the overall coding process and shows the steps described in this section.

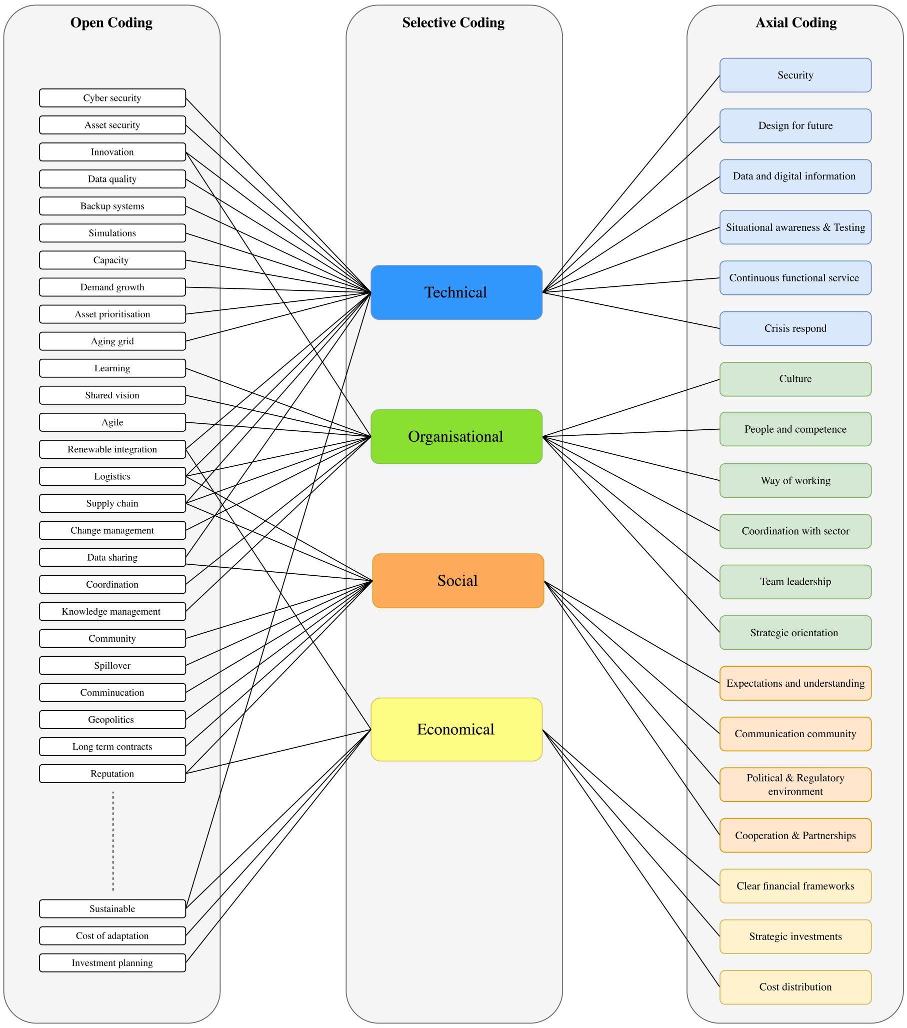


Figure 4.3: Visualisation of coding phase

4.3 Development

The initial phase of the developmental process focused on establishing the hierarchical structure. This resulted in the representation shown in Figure 4.4 on the next page. Although this configuration provided a clear overview of the identified criteria, it could not serve as the final design. The strictly hierarchical representation did not sufficiently satisfy the established design requirements.

Consequently, several alternative approaches for representing the framework were explored. First, methods commonly applied within the asset management domain were considered. Asset management, closely connected to the concept of resilience, emphasises lifecycle-oriented decision-making, particularly in relation to an organisation's existing technical state (asset portfolio) and its exposure to external disruptions [65]. In the domain of asset management, a range of frameworks is employed to convey information in an effective manner. Nevertheless, this did not directly contribute to the design of the study.

In addition, quality management principles were also examined, including ISO 9001 and the Plan–Do–Check–Act (PDCA) cycle. This gave insights for the longitudinal applicability (DR7) and application of the framework, but not for the design. This also applies to single-loop and double-loop learning as a potential representation of organisational learning mechanisms [7]. In short, single-loop learning focuses on "doing things right," while double-loop learning challenges whether we are "doing the right things". Good points to bear in mind when working with the framework.

Furthermore, a number of conceptual and analytical models were evaluated. The cornerstone model [33]; Business Process Modelling (BPMN) as a tool for mapping organisational processes. Several existing framework visualisations were also analysed, including the ARUP resilience circle [8]. However, such representations generally present frameworks as segmented blocks or layered structures. While visually structured, these approaches fail to adequately capture the complex interrelationships and overlaps between the identified criteria, and therefore remain conceptually similar to the hierarchical representation shown in Figure 4.4 on the next page.

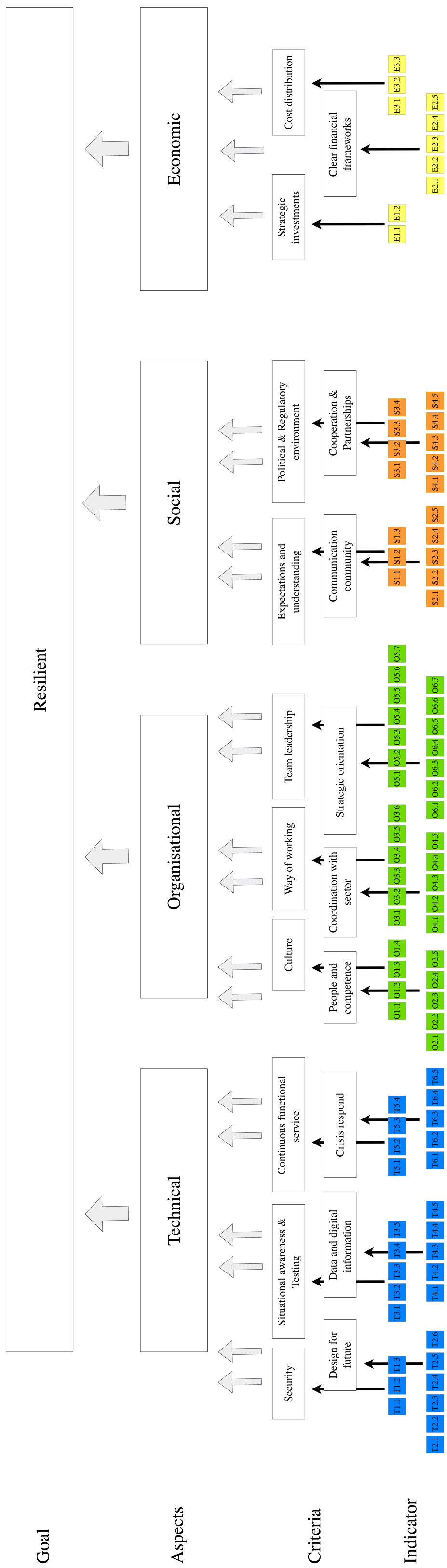


Figure 4.4: Conceptual framework, based on the hierarchical structure, filled with criteria and indicators, details see Appendix E

Following a series of brainstorm sessions and the analysis of the interview data, several alternative visual representations for the framework were explored. These included hierarchical models, layered architectures, and network-based structures. Ultimately, a Venn diagram was selected as the most appropriate enhanced representation of the framework, as it most effectively conveys the non-linear and interdependent nature of resilience. In contrast to hierarchical depictions, the Venn diagram highlights interconnections and mutual dependencies between the criteria, which emerged as a dominant theme across the empirical data.

The resulting framework representation is shown in Figure 4.5. The criteria have been arranged in aspects, after which the criteria themselves were positioned to reflect areas of conceptual overlap based on shared functions, responsibilities, and dependencies. This design solution reinforces the premise that resilience is not constructed from isolated components, but from dynamically interacting elements.

For example, the organisation of *Data and Digital Information* (T3) is a fundamental enabler for *Situational Awareness & Testing* (T4), as reliable and structured data are a prerequisite for effective monitoring, scenario analysis, and stress testing. Similarly, the interaction between *Cooperation & Partnerships* (S4) and *Coordination with Sector* (O4) reflects the inter-organisational dimension of resilience, which is further connected to *Strategic Orientation* (O6), indicating that external alignment and long-term strategic direction mutually reinforce each other.

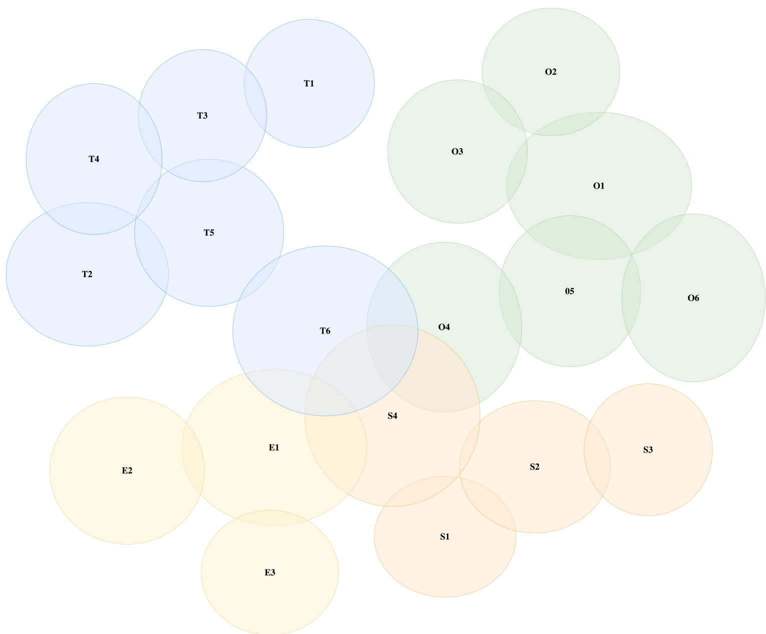
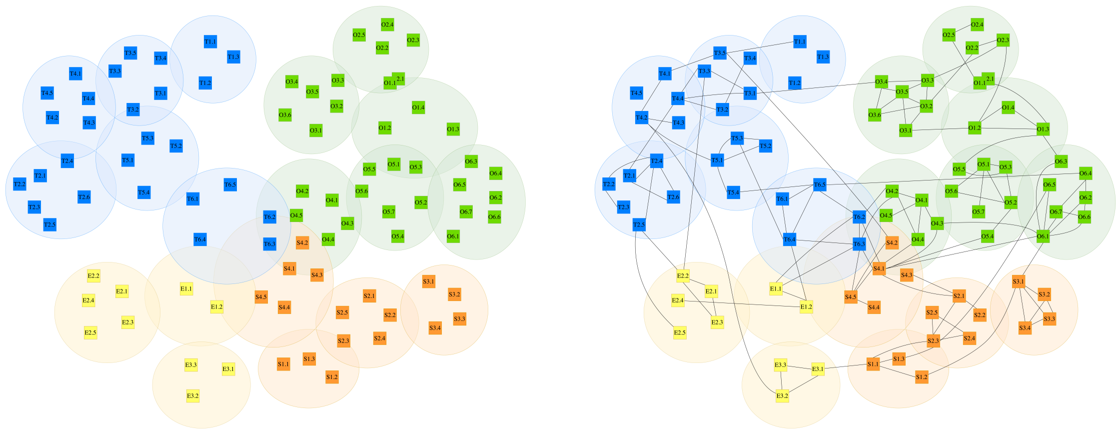


Figure 4.5: Framework with criteria transformed into a Venn diagram structure

This visual configuration does not imply that any single criteria is more dominant or that one cannot exist without the others; rather, it communicates that the criteria operate as reinforcing mechanisms within a broader resilience system. Because it was not possible to determine a priori which elements are more significant, it was decided to maintain the size of the circles at virtually the same level, thereby avoiding an unintended hierarchy and preserving analytical neutrality. The minor graphical modifications were introduced to enhance visual cohesion, balance, and interpretability of the framework.

In a subsequent refinement step, the indicators were incorporated into the criteria, thereby extending the framework from a high overview to a detailed structure. This expansion serves to accentuate the comprehensiveness of the assessment, as it enables the framework to capture nuance and granularity beyond the original set of 19 criteria. The enriched model is illustrated in Figure 4.6a and allows for analysis at both the criteria and the indicator level.

Furthermore, the inclusion of indicators enabled the identification and visualisation of interconnections not only between criteria, but also between indicators. The relationships that have been established originate from logical reasoning and contextual interpretation, primarily derived from the interviews and observations. The relationships between indicators within a criteria are logical because the reasoning was previously reversed in order to form a set of criteria. While the present study did not empirically validate these relationships, their explicit representation (see Figure 4.6b) provides a structured interpretation of the complex, multi-dimensional nature of resilience and offers a foundation for future empirical investigation.



(a) Framework with indicators

(b) Framework with indicators and connections

Figure 4.6: Frameworks, based on the Venn diagram structure, filled with criteria and indicators, details see Appendix E and for an enlarged version Appendix F

4.4 Application of the Framework

Before evaluating the extent to which the framework satisfies the design requirements, it is important to briefly clarify how the framework is intended to be used in practice. The framework is designed as a structured assessment and reflection tool that supports organisations in analysing their resilience capabilities systematically and iteratively.

Prior to the assessment process, a consensus definition of resilience must be established. It is recommended that the system-oriented definition outlined in Section 3.1.3 is used. The assessment process starts at the criteria level, where organisations evaluate their current position for each of the 19 criteria using the associated indicators as guiding elements. These indicators operationalise the criteria and provide concrete points of reference for judgement and discussion.

For the scoring, the maturity model is adapted from an established capability maturity model, the Systems Security Engineering Capability Maturity Model (ISO/IEC 21827:2008) [64]. The SSE-CMM® comprises five maturity levels and was originally developed for security engineering. It has been adapted to better reflect the context of this study. The model describes five levels of maturity, ranging from "Not Aware" to "Excellent", to assess an organisation's level of compliance or performance, as shown in Table 4.1. This enables organisations to perform a self-assessment and assign scores accordingly [1].

Table 4.1: Scoring system for assessment

Score	Description
0 Not Aware	No recognition of the requirement; no evidence of commitment.
1 Aware	Requirement identified; evidence of intent to progress exists.
2 Developing	Systematic and consistent approaches are being progressed with credible, resourced plans.
3 Competent	Requirements are systematically and consistently achieved, with only minor inconsistencies.
4 Excellent	Practices consistently exceed requirements, align with leading international practice, and demonstrate a mature continuous improvement culture.

Both representations of the structures, hierarchically and Venn diagrams, are recommended in order to demonstrate the methods by which resilience can be graphically represented and to indicate complexity. The framework can be applied either in a comprehensive manner, covering all aspects and criteria, or in a more focused way by selecting specific criteria and indicators that are most relevant to the organisation's strategic objectives or current challenges. This modularity allows the framework to be adapted to different organisational contexts and resource constraints, while preserving its analytical consistency.

Moreover, the interconnected structure of the framework encourages users to consider the interactions between criteria rather than treating them as isolated components. The visualisation supports this process by explicitly highlighting overlaps and reinforcing the multi-dimensional nature of resilience. As a result, the framework not only functions as a diagnostic instrument but also as a discussion tool that facilitates cross-departmental dialogue and shared understanding among stakeholders.

Finally, because the framework is intended for repeated use over time, it enables organisations to track developments, evaluate the effectiveness of implemented interventions, and continuously refine their resilience strategies. This longitudinal application supports organisational learning and ensures that resilience management remains an ongoing and adaptive process. This also implies adjusting and improving the framework to the challenges appearing over time.

5

Evaluation Results and Discussion

This chapter presents the evaluation and discussion of the proposed resilience framework. The evaluation is conducted through two lenses. First, the framework is assessed against the predefined design requirements to determine the extent to which the intended functional, usability and methodological objectives have been achieved. Second, evaluation interviews with experts to capture stakeholder perceptions, practical relevance and contextual fit. This chapter ends with a discussion about the process and the outcome.

5.1 Alignment with Design Requirements

The developed framework largely fulfils the design requirements formulated in Section 3.4. The functional requirements DR1–DR3 are addressed through the integrated structure of the framework and its supporting assessment logic. In particular, the framework provides a shared and explicit definition of resilience (DR1), while adopting a holistic TOSE perspective (DR2). Furthermore, the framework enables a process-oriented and iterative mode of application (DR3), allowing organisations to repeatedly assess, reflect, and refine their resilience posture over time.

With respect to the structural requirements DR4–DR6, the framework demonstrates strong compliance. The visual representations and layered composition support readability and accessibility (DR4), while the design of criteria and indicators enables flexible use and selective application (DR5). The framework simultaneously supports high-level overviews and in-depth analysis (DR6), as evidenced by the progressive refinement from criteria to indicators.

Regarding the contextual requirements, DR7 is supported through the longitudinal applicability of the framework. The design allows repeated assessments across time, facilitating the monitoring of resilience development and organisational learning. DR8 (maturity-based evaluation) is satisfied, as the study applies a structured maturity model in which criteria and indicators are assessed across clearly defined, ordinal maturity levels. Although the evaluation is qualitative in nature and does not involve numerical aggregation, it enables a systematic maturity-based assessment of organisational practices. As such, the approach supports comparative interpretation of maturity levels. However, for DR9 (integration with organisational routines), no definitive conclusion can be drawn at this stage. Due to time constraints and the absence of extensive external validation, this aspect could not be empirically evaluated within the scope of the present study. Their full validation therefore remains a key direction for future research and practical application.

Overall, the framework demonstrates strong alignment with the formulated design requirements and provides a coherent and theoretically grounded tool for analysing resilience, while clearly identifying avenues for further development and validation. It should be acknowledged that the researcher's background in mechanical engineering and a minor in asset management influenced the implementation and evaluation of the framework. Familiarity with asset-intensive systems and prevailing asset management practices facilitated a nuanced understanding of sector-specific challenges and supported the identification of practically relevant criteria and indicators. At the same time, in order to avoid an overly narrow technical framework, it was necessary to engage in conscious reflection regarding the technical background. Concurrently, the researcher's experience in asset management facilitated the immediate recognition of the significance of organisational structures. This combination of technical knowledge and organisational insight was further strengthened during the master's degree, which focused on the integration of technical and organisational perspectives. This helped the researcher to maintain a broad socio-technical view of resilience. This awareness was actively considered throughout the design and evaluation process to mitigate bias and to maintain alignment with the broader socio-technical scope of resilience.

5.2 Evaluation by External Experts

In addition to evaluating the design requirements, the study also examined how the framework is received by the individuals who will be working with it in their professional practice. Semi-structured interviews were the chosen method again. The interviews were held at the end of December 2025 and beginning of January 2026. An overview of the respondents is presented in Table 5.1. One of the respondents had also participated in earlier stages of the study, while the other was not previously involved. This deliberate selection allowed the framework to be reviewed both by an expert familiar with the research context and by a new user encountering the framework for the first time. This combination provided insight into how the framework evolved in response to earlier findings, while simultaneously offering an initial indication of its clarity, usability, and interpretability when applied by a first-time user.

Table 5.1: List of respondents in evaluation

Respondent	**Role:**	**Experience (years)**
Respondent 4	Director of Asset Management	15+
Respondent 7	Resilience & Adaptation Manager	10

The interview protocol used for this purpose is provided in Appendix C. The interview data were analysed and based on the summarised data in Appendix C.3. The interviews provided a strong external validation of the proposed resilience framework

with respect to its novelty, relevance, and practical applicability. Several observations are worth noting:
First, that structuring resilience into clearly defined criteria supported by indicators constitutes a meaningful, conceptually sound and innovative approach, which enables a systematic approach.
Second, it is mentioned that the framework's design and scope highlight its comprehensiveness beyond the technical domain and its ability to incorporate organisational, economic, and social dimensions that are often insufficiently considered in existing practice. Satisfying the requirement of conceptual coherence and theoretical alignment with professional practice.
Furthermore, the visual representation of the framework is identified as a key strength. The graphical mapping of interdependencies can significantly improve stakeholder understanding of resilience by making the inherent interconnectedness between domains visible. It was pointed out, however, that it is important to consider the purpose of a conversation and which details are included.
In addition, it is noted that the current formulation of criteria, indicators, and descriptions strikes an appropriate balance between guidance and flexibility, enabling organisations to adapt the framework to their specific operational context.
Finally, the framework is a strong starting point for organisational implementation. It enables organisations to identify high-impact focus areas and prioritise actions by identifying "low-hanging fruit".

5.3 Results Discussion

This section discusses the framework's development, positions the proposed framework relative to existing approaches, the framework's applicability, and reflects on the role of Design Science Research (DSR) in its development.

The first action that was taken was to get a consensus regarding the definition of resilience. By deconstructing resilience into the *of What*, *to What*, and *is What* questions, a focused meaning is established. After analysing resilience, it appears that it may not be necessary to use a universal definition. However, the methodology has resulted in a system-oriented definition and a practical implementation that greatly assists in shaping perceptions. This is important because it reveals the underlying assumptions and enables meaningful conversations to be initiated. The definition reflects a deliberate trade-off between generality and specificity. Excessive abstraction would undermine its practical usability, whereas overly detailed definitions would limit transferability and risk premature closure on resilience interpretations.

With this as a starting point, work on the framework commenced following a defined approach and methodological implementation. Alternative options were also considered, such as structuring the framework according to resilient response stages (the ability to anticipate, absorb, recover quickly from, adapt to, and learn from disruptive events [66]) rather than according to the TOSE structure. The decision to work with TOSE is based on its widespread recognition in the literature and its limited practical use, which increases its added value. It has also been found

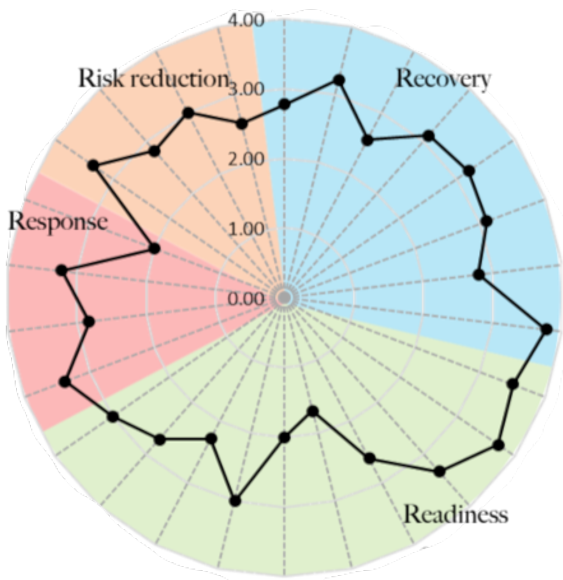


Figure 5.1: Resilience maturity assessment spider chart by stages: risk reduction, readiness, response, recovery (Electricity Engineers' Association (EEA))

that the 'stages' division requires the indicators to be determined in advance, which would result in a lot of overlap in the findings. In the evaluation interview with R7, a model from the Electricity Engineers' Association of New Zealand was presented [1], in which the stage-based approach is elaborated. The model divides the assessment into four stages: risk reduction, readiness, response, and recovery (see Figure 5.1). This so-called "4R theory" was originally proposed by the American crisis management expert Robert Heath [70]. It is comparable to the bow-tie method, which examines how risk can be managed by analysing preventive measures before a disruptive event and recovery actions afterwards. A limitation of this approach is that it focuses primarily on crisis management and disruptive events. As mentioned earlier, this stage-based model also requires a systematic method for selecting and structuring the underlying criteria. Such a method could, for example, follow the same structural approach applied in the development of the present framework, indicating substantial overlap between the two approaches. A mixed matrix approach could therefore be explored in future research. Although comparable models already exist [59], this study deliberately focused on a single approach in order to observe how new forms and structures would emerge from the framework design process.

After reviewing alternative approaches, the choice for a TOSE-based, multi-criteria assessment was motivated by the objective of this study to support organisational sense-making rather than crisis-phase optimisation. Stage-based models primarily structure responses around disruptive events, whereas the present research aims to expose structural vulnerabilities and interdependencies that exist prior to, during, and beyond such events. This aligns more closely with the goal of resilience as an ongoing organisational capability rather than an episodic response mechanism.

With respect to the choice of approach for measuring resilience, Kott et al. distinguish between two main approaches: metric-based and model-based [44]. The metric-based approach was selected, as model-based approaches typically rely on realistic, interactive models of real-world situations for practice and assessment. Developing such models requires prior knowledge of which elements should be observed and measured. Identifying these elements constituted part of the knowledge gap addressed by this study, so this was not an option. In retrospect, this choice proved effective, as the metric-based approach enabled an open and exploratory identification of resilience-related vulnerabilities and capacities across organisational layers. Rather than constraining the analysis to predefined scenarios or response mechanisms, the approach supported iterative refinement of resilience criteria as empirical insights emerged. In addition, there is a danger in becoming too focused on specified resilience because increasing resilience of particular parts of a system to specific disturbances may cause the system to lose resilience in other ways [29]. A metric-based approach was therefore considered more appropriate, as it allows a broader exploration of vulnerabilities and capacities without prematurely constraining the assessment to specific scenarios or response mechanisms.

A central outcome of this study is that resilience assessment in practice cannot be reduced to a simple compliance question such as “What is the organisation’s resilience score?” This baseline scoring was something that most respondents ideally wanted to see. The framework’s real value may not lie in its immediate application, but in demonstrating the complexity of resilience and showing that a systematic assessment that is both methodologically feasible and theoretically sound can provide a starting point. However, it needs to be adapted further to meet the needs of stakeholders in the sector. As noted by a respondent, a framework may significantly improve situational awareness, but “you cannot say at the end of the day you are resilient or not.” This observation directly supports the methodological choice adopted in this study. Before resilience can be meaningfully quantified, it must first be clearly qualified: organisations need to establish what aspects of resilience are relevant in their specific context and why they matter, before determining how they should be measured. Consistent with this reasoning, the selection between qualitative and quantitative approaches should be driven by the needs and objectives of the framework’s users [17]. In the present study, the framework and its associated tables are therefore intentionally qualitative in nature. They provide a structured means of identifying, discussing and interpreting resilience-related aspects, criteria and indicators. This approach aligns with broader resilience assessment literature, which emphasises that stakeholders themselves must judge whether particular aspects or criteria of resilience are relevant at a given moment and whether they have been sufficiently addressed. Some of these judgments can be made relatively straightforward, while others remain inherently ambiguous and context-dependent [68]. The framework is designed to support this judgment process by making assumptions explicit, encouraging reflection, and structuring collective decision-making.

In this way, the framework is deliberately grounded in the organisation’s own expertise rather than in external auditing logic. The empirical findings indicate that companies increasingly understand what auditors seek and can “mislead any auditor if one wishes to do so," which ultimately undermines genuine organisational learning. To counter this effect, the framework is designed to elicit authentic internal knowledge, promote honest reflection, and foster a culture in which the primary objective is strengthening resilience rather than merely achieving compliance or accumulating "green ticks." At the same time, the framework explicitly recognises resilience as a dynamic and evolving concept. The relevance of specific risks, vulnerabilities, and resilience measures changes as the organisation and its operating environment develop. Consequently, the value of the framework does not lie in a fixed or exhaustive list of criteria and their scoring, but in providing a structured mechanism for continuously reviewing, expanding and refining that list, as the risks and vulnerabilities evolve. This enables organisations to systematically incorporate new insights, emerging threats and operational lessons over time.

This orientation reflects the core principles of Design Science Research. Rather than optimising for theoretical elegance or abstract performance metrics, the artefact was iteratively shaped through stakeholder input, practical constraints, and contextual relevance. The framework therefore embodies the DSR logic of building a useful artefact that addresses a real organisational problem, while simultaneously contributing structured knowledge to the resilience literature. This design orientation reflects the core logic of Design Science Research, in which artefacts are evaluated not solely on predictive accuracy or measurement precision, but on their utility in addressing real organisational problems. The framework was therefore intentionally designed to prioritise usability, interpretability, and adaptability over optimisation, acknowledging that resilience is an evolving construct shaped by organisational context and stakeholder judgement.

6
Conclusion

This thesis contributes to resilience research by operationalising resilience for critical energy entities through a structured, multi-criteria framework grounded in the Technical, Organisational, Social, and Economic (TOSE) dimensions. It advances theory by translating fragmented resilience concepts into a coherent and assessable structure. From a practical perspective, the framework provides organisations with an actionable instrument for identifying vulnerabilities, supporting strategic and operational decision-making, and embedding resilience into everyday practice. Methodologically, the study demonstrates the applicability of Design Science Research beyond its traditional IT focus, illustrating its value in developing and validating complex management frameworks in socio-technical contexts.

6.1 Answering the research question

SQ1: **What does the term resilience mean for critical entity energy?**
Extensive research has been conducted into the significance of resilience and the specification of the concept for the sector. First, an analysis was carried out of how resilience is applied within the relevant context. To achieve this, two fundamental questions were addressed: the nature of the entity under consideration (resilience of what), and what resilience should be directed towards (resilience to what). From this contextual foundation, the question of what resilience is has been examined. The conclusion is that a system-oriented definition, supported by its conceptual characterisation and graphical representation, provides the most comprehensive understanding of resilience. Resilience is thus defined as "the ability of a socio-technical-environmental system to sustain, improve, and innovate its key functions—by absorbing, reacting to, recovering from, adapting to, or reorganising in response to chronic stresses, abrupt shocks, and disruptions," and is characterised by both reduction and recovery capabilities.

SQ2: **What do industry stakeholders consider important when developing a resilience framework?**
The interviews and review of literature indicate that there are only a limited number of strong requirements that stakeholders consistently consider important when developing a resilience framework. Nevertheless, based on the combined insights from both sources, nine design requirements have been formulated. These requirements are grouped into three complementary categories: functional, structural, and contextual. The functional requirements primarily define what the framework must

accomplish in order to address the identified challenges (shared definition, integrated TOSE perspective, and process-oriented and interactive assessment). The structural requirements specify how the framework should be constructed and which components it should include (readable & accessible structure, modular design, and overview and detail support). Finally, the contextual requirements reflect what the intended users need from the framework in their daily practice and organisational environment (longitudinal applicability, maturity-based evaluation, and integration with Organisational routines).

SQ3: **Which criteria and indicators can be identified to assess the aspects of resilience?**
Three methodologies were employed in this study to gather data: review of literature, observations, and interviews. This mixed-method approach systematically identified resilience criteria and indicators through the combined analysis of literature, industry observations, and semi-structured interviews with academic and industry experts. Using an inductive coding strategy, all data sources were analysed through open coding, allowing relevant concepts, criteria, and indicators to emerge directly from both theory and practice. This analysis also examined the possible influences of Dutch legislation and regulations currently under development.

SQ4: **How can the criteria be structured into a practical multi-criteria resilience framework?**
First, a selection was made from all criteria and indicators that had been identified. This was done following the coding strategy, continuing from the open coding phase. This deviates from purely inductive coding and instead applies a combination of inductive and deductive coding. Consequently, a total of 19 criteria and 89 indicators were identified. Building on the established design requirements, a framework was developed using a hierarchical multi-criteria architecture. Through an iterative process of design and refinement, the framework was shaped to balance conceptual rigour with practical usability. During this process, an alternative approach was explored and adopted, leading to the final framework presented in this study, with a Venn diagram structure. As the initially selected hierarchical multi-criteria architecture by itself did not satisfy all design requirements.

SQ5: **How does the proposed framework enable a comprehensive resilience assessment for organisations within critical energy entities?**
The proposed framework was evaluated against the established design requirements and externally validated through expert interviews. The evaluation demonstrates that the framework satisfies nearly all requirements; the single unmet requirement results from deliberate time and design trade-offs rather than conceptual shortcomings. Experts confirm the framework's relevance, novelty, and practical usability, also highlighting the importance of tailoring the level of detail to the specific purpose of the assessment and the organisational context in which it is applied. Crucially, the framework's value extends beyond its specific set of criteria and indicators. It introduces a structured assessment logic that supports continuous review, refinement, and extension, enabling organisations to systematically integrate new insights,

emerging threats, and operational learning over time. As such, the framework facilitates a comprehensive resilience assessment as an ongoing organisational practice rather than a one-off evaluation.

With this, the study provides a clear answer to the main research question:
How can organisations in the critical entity, energy, perform a comprehensive resilience assessment?

Organisations can perform a comprehensive resilience assessment by first establishing a shared understanding of resilience. This understanding is subsequently operationalised through a structured multi-criteria framework that translates resilience into clearly defined aspects, criteria, and indicators. The framework enables systematic assessment, while explicitly acknowledging interdependencies between the aspects through a complementary Venn-based structure. Together, these elements support a coherent, transparent, and adaptable approach to resilience assessment that can evolve with changing organisational and external conditions. The primary value of the framework lies not only in the specific set of criteria and indicators it contains for the assessments, but in the structured mechanism it provides for continuous review, expansion, and refinement. This allows organisations to systematically incorporate new insights. In doing so, this study demonstrates that a comprehensive resilience assessment is not only methodologically sound but also practically achievable within real-world critical energy organisations.

In conclusion, this study delivers both a rigorous conceptual foundation and a practical assessment tool that together support organisations in the critical energy sector in conducting systematic, comprehensive, and adaptive resilience assessments.

6.2 Implications of the research

Academic
This research contributes to the academic discourse on resilience by advancing the concept of resilience from a predominantly conceptual construct toward an operational and assessable capability. Rather than framing resilience merely as the ability to return to a prior state, the proposed framework emphasises adaptive improvement. Recognising that recovery to an undesirable baseline does not constitute meaningful resilience. By structuring resilience into explicit aspects, criteria and indicators, this study offers a concrete methodological foundation for future empirical work. The framework therefore supports theory development by enabling systematic observation, comparison, and refinement of resilience practices across organisations and contexts.

Furthermore, the study demonstrates the value of combining Design Science Research with qualitative inquiry for developing management instruments in complex environments such as critical entities. This methodological contribution provides a replicable approach for scholars seeking to translate abstract concepts into actionable organisational tools.

Organisational
For practitioners, the framework's most significant practical value lies in its ability to facilitate organisational dialogue and embed resilience thinking into everyday practice. By providing a shared language and a structured representation of resilience, the framework facilitates communication among strategic, operational, and technical stakeholders, serving as a boundary object that aligns perspectives and fosters consensus-building.

This contribution directly responds to the gap identified in recent literature. As noted by Parag et al. (2026), "in this emerging energy landscape, resilience cannot be understood or measured through a one-size-fits-all lens," yet "the absence of scalable frameworks makes it difficult to benchmark performance, compare investments, or institutionalise resilience into regulatory planning" [55]. The proposed framework addresses this challenge by offering a context-sensitive yet structurally consistent assessment approach that enables organisations to interpret resilience according to their own operating environment while maintaining coherence and comparability across organisational levels.

The framework enables organisations to systematically assess resilience across interconnected aspects, thereby supporting strategic and operational decision-making in asset-intensive energy systems.

6.3 Research Limitations

Several limitations should be acknowledged, as in this research choices were made around scoping and process. First, the empirical evaluation of the framework was constrained by the time of the project and the availability of respondents, resulting in a limited number of expert interviews during the evaluation phase. While the feedback strongly supports the framework's relevance and usability, broader application across different organisational contexts would further strengthen its external validity. In addition, you could argue about the selected focus group of asset managers. The expertise of OHROS Consulting Group is asset management in asset-intensive industries. Therefore this became the lens of the project. If another background and perspective had been chosen result could have been different. Asset management is invariably associated with a technical standpoint. Adoption of a more community- and user-based approach to energy will change indicators, and with it, most likely, the results.

Secondly, the framework remains primarily qualitative in its current form. Although respondents expressed strong interest in quantification and maturity scoring, the development of a fully validated quantitative scoring model was beyond the scope of this thesis. A further consequence of qualitative research is that the results obtained are highly dependent on the individual responsible for their analysis.

Thirdly, this study highlights the importance of the learning effect in resilience assessment. As the operating environment evolves rapidly, the framework requires regular revision and continuous refinement. At the same time, the framework itself does not prescribe how assessment outcomes should be embedded within organisational processes or translated into concrete managerial action.

6.4 Generalisability

The generalisability of the findings and the proposed framework is subject to several constraints.

First, the limited stakeholder pool may reduce generalisability, particularly as the evaluation primarily involved asset management professionals from asset-intensive energy organisations. Their shared professional background influences how resilience challenges are perceived and prioritised, and alternative stakeholder perspectives could lead to different emphases within the framework. The aimed sample size for qualitative interviews is ideally around twelve respondents [34]. However, due to the substantial input of observation data, it is not expected that more interviews within the same pool would yield different results.

Generalisability to other critical entities has not been empirically assessed. It is anticipated that the proposed framework can be transferred with relatively limited adaptation to asset-intensive critical entities, such as transport and drinking water systems. In these sectors, the resilience of what remains is largely centred on physical assets and supporting organisational systems, while the resilience to what predominantly concerns operational disruptions and long-term stresses. As a result, the core TOSE structure and multi-criteria logic are expected to remain largely applicable.

For conditionally transferable sectors, such as telecommunications and digital infrastructure, the framework may require targeted adaptation. While these sectors remain asset-intensive, the critical functions increasingly rely on intangible assets, information flows, and cyber-physical interdependencies. This shifts both the resilience of what and the resilience to what, necessitating refinement of criteria and indicators.

In contrast, low transferability without substantial redesign is expected for sectors such as banking and food. In these contexts, the core system boundaries, dominant vulnerabilities, and societal dependencies differ fundamentally.

Overall, these distinctions indicate that the framework's transferability is primarily driven by alignment in the resilience of what and resilience to what dimensions, rather than by sector classification alone. Another important factor is the current methods used and legislation. These vary from country to country, as each country interprets the guidelines in its own way. As a result, the framework may not be generalisable because it does not match the current method in use or because it is not in line with the applicable guidelines.

6.5 Future Work and Recommendations

While this study contributes a validated and structured resilience assessment framework for critical entities in the energy sector, several avenues for future research and practical development remain.

From a practical perspective, OHROS is strongly encouraged to embed the framework within its advisory practice as a structured diagnostic instrument. In particular, the framework can be employed in facilitated workshops to stimulate multi-level organisational dialogue on resilience, bridging strategic, tactical, and operational perspectives. Furthermore, its use as an early-stage diagnostic tool in advisory trajectories would enable the systematic identification of high-impact vulnerabilities prior to the formulation of intervention strategies. Repeated application across a diverse portfolio of clients would allow OHROS to iteratively refine criteria and indicators, thereby strengthening both the framework's empirical grounding and its consultancy value.

As an initial step in applying the framework, organisations are recommended to first review the full set of criteria at a high level, without attempting immediate scoring or prioritisation. This enables stakeholders to develop a shared overview of the breadth of resilience-related aspects captured by the framework. Subsequently, organisations can distinguish between criteria that are well understood and actively addressed, and those for which knowledge, ownership, or visibility is limited. The latter typically represent areas of latent vulnerability and are therefore likely to offer the greatest potential for improvement. Focusing follow-up efforts on these less-understood criteria provides a pragmatic and learning-oriented starting point for deeper analysis and targeted resilience interventions.

For the wider critical energy sector, the framework offers a shared structure for discussing resilience without imposing uniform definitions or metrics. Sector actors are encouraged to apply the framework collaboratively, for example through joint workshops or sector platforms, to identify common vulnerabilities, interdependencies, and resilience challenges that extend beyond individual organisations. Such collective application could support cross-organisational learning and inform sector-wide investment and coordination strategies.

Future research could focus on the longitudinal application of the framework within organisations. Conducting repeated assessments over time would allow researchers to analyse how organisational resilience develops, how implemented improvement measures affect resilience-related outcomes, and how assessment results influence strategic and operational decision-making. Such longitudinal studies would contribute to the conceptualisation of resilience as a dynamic organisational capability rather than a static state.

Second, future work should aim to operationalise the framework into a quantitative maturity-based assessment model. This would involve the development of transparent scoring mechanisms, the weighting of criteria and indicators, and the establishment of benchmarking procedures across organisations or sectors. Such an extension would significantly enhance the framework's applicability for prioritisation, performance comparison, and evidence-based investment decisions, particularly in consultancy and policy contexts.

Third, an interesting research direction lies in integrating the framework with a stage-based or evolutionary resilience model. A hybrid approach would allow organisations not only to assess the presence of resilience-related capabilities across multiple dimensions, but also to position themselves along a developmental trajectory of resilience maturity. This would support roadmap development and enable more targeted, phased improvement strategies.

Finally, although this research focused on the energy sector, the framework was intentionally designed to be transferable. Future studies should therefore examine its applicability within other critical entities, such as transport or drinking water systems, identifying necessary sector-specific adaptations while preserving the underlying conceptual structure. Such cross-sectoral validation would further strengthen the generalisability and relevance of the framework.

6.6 Personal Reflection

Writing this thesis has also been a learning experience for me personally as a researcher, professional, and person.

First, I would like to reflect on the development of the past six months. Looking back, it has been a very short period in which a lot has happened. Just before the first month was over, I drew up a schedule that followed a nice waterfall progression. This is not how the following months turned out. Several parts were delayed and overlapped. Flexibility in the schedule was particularly important when it came to the interviews. Recruiting participants via email proved to be more time-consuming than expected.

Secondly, I also learned a lot from conducting the interviews. While the first interview was somewhat awkward and did not immediately have the desired impact, I noticed that it became easier as I progressed. This growth led to greater depth and better interaction. As a result, the interviews became more interactive, which made my perception of the information I was gathering sharper and more nuanced. It was inspiring to see participants directly translating insights into their own vision and the broader business context. This confirmed for me the value of the process and the impact of proper conversation. At the same time, I received more than once feedback that I sometimes present this wealth of information and the process of collecting it in an overly abbreviated manner. I will continue learning to seek a finer balance to present my observations more fully.

Thirdly, a few words about the use of AI. This is still relatively new, so it is good to reflect on it. AI (in this case only ChatGPT) helped to improve sentences. Entering my own sentence(s) into Chat and then demanding that it remain close to the original text while improving clarity and academic tone. Chat was also a great help with some tables and figures in LaTeX format. All analytical choices, interpretations, and conclusions remained the responsibility of the researcher; AI was used strictly as a linguistic and formatting support tool.

Finally, now that it is almost over, I am pleased with how I have been able to demonstrate my scientific competence as an independent academic researcher, enabling me to carry out a research process, collect concepts, insights, material and literature, and turn this into new insights and construct them in an academically sound manner.

A
Literature Search

The focus of this study is not on conducting an extensive literature review. The literature review provides the basis for understanding the current state. Therefore, a flexible rather than strictly systematic approach was adopted to capture the full scope of relevant developments. This means the review is not fully according to the PRISMA guidelines [49]. However, the steps from the guideline are used to provide structure. These steps are identification, screening, eligibility, and inclusion.

Due to the significant increase in publications in recent years, backward snowballing is mostly applied. This made it easier to find good and relevant information. Literature was searched using the following search terms using Boolean operators like ("resilience assessment") AND "critical infrastructure":

- Resilience
- Defining resilience AND technology
- Asset management AND resilience
- Critical infrastructure AND resilience
- Energy systems AND resilience
- Resilience framework
- Resilience assessment framework
- Resilience criteria
- Resilience assessment AND critical infrastructure

“Cyber”-related research is excluded from the search because it brought up studies that were too specific. This is done with AND NOT (“cyber”). This search is done in multiple databases: Science Direct, Research Gate, EU database, institutions and via search engines such as Google.

The decision to search for the term "infrastructure" as opposed to "entities" is predicated on the observation that the former is utilised with greater frequency. In the initial search for entities, the number of relevant results was found to be almost non-existent.

B

Participants information ITAMS

International Transmission Asset Management Study (ITAMS) is a learning collaborative that shares knowledge and best practices. Twelve participants from the energy transmission sector (TSOs), operating globally and managing grids with an average length of 40,000 km, took part in the most recent cycle (2024–2025) [40].

As a host of ITAMS, OHROS Consulting Group provided access to all available data and information (e.g. qualitative and quantitative data, best practice interviews, work group webinars). This included the recordings and materials of the conference that concluded last cycle (held in October 2025), where in addition to the twelve participants who took part in the cycle, three additional participants attended (see B.1).

TSOs operate under mutual market forces and are therefore not in competition with each other. Emphasising the value of the knowledge they share, as commercial purposes do not drive it.

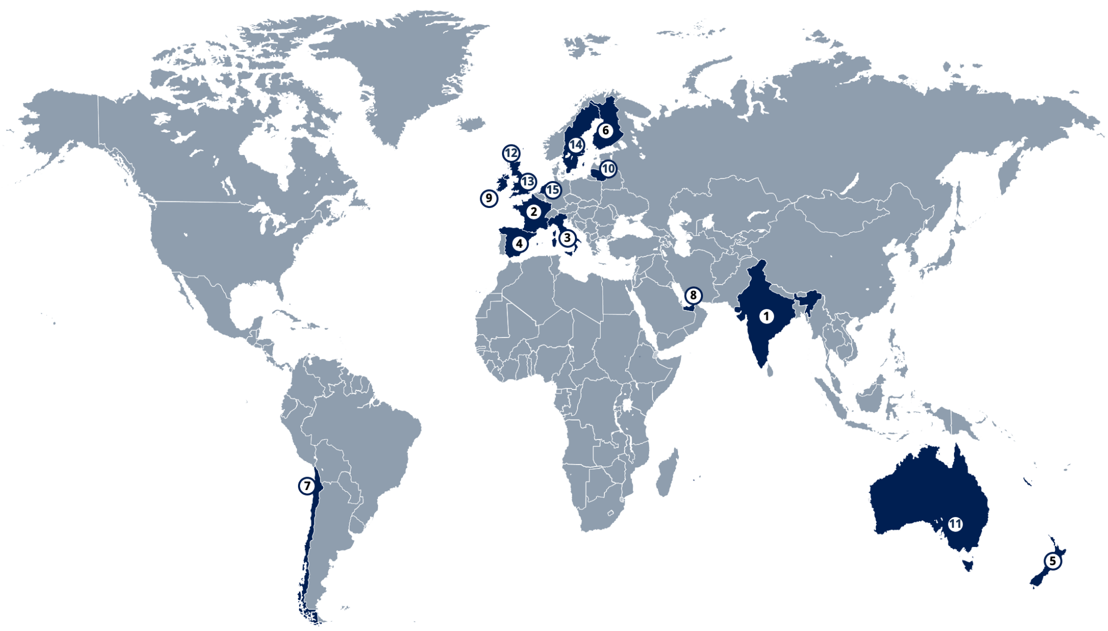


Figure B.1: Global outlook participants ITAMS

Table B.1: List of participants ITAMS

Participant	**Country**
Participant 1	India
Participant 2	France
Participant 3	Italy
Participant 4	Spain
Participant 5	New Zealand
Participant 6	Finland
Participant 7	Chili
Participant 8	United Arab Emirates
Participant 9	Ireland
Participant 10	Lithuania
Participant 11	Australia
Participant 12	Scotland
Participant 13	United Kingdom
Participant 14	Sweden
Participant 15	Netherlands

C
Expert Interviews

The purpose of the interviews is to gain insight into how internal and external factors contribute to or detract from the resilience of the company. The interviews serve to validate the theoretically identified criteria and supplement them with empirical insights. The interviews support answering SQ2, SQ3 and later SQ4. Semi-structured interviews will be conducted among different direct industry stakeholders and academic experts.

C.1 Interview Protocol Analysis

The interviews will last approximately 45 minutes and follow the structure outlined below:
Introduction (±5 minutes)
A short introduction of the researcher and the purpose of the study will be provided. The goal, structure, and expected timeline of the interview will be explained, and informed consent will be confirmed before recording begins.

Part 1: Context and Framing (±10 minutes)

- Provide a brief explanation of the design framework, including the four aspects of resilience: *technical, organisational, social*, and *economic*.
- Present the preliminary list of resilience criteria derived from the literature and initial observations.
- Discuss the company's current approaches or models related to resilience, focusing on what is working well and what may be missing or could be improved.

Part 2: Criteria and Indicator Identification (±15 minutes)
This section aims to identify which criteria are considered most and least relevant for the organisation.

- Discuss the criteria and indicators used currently by the company.
- Discuss the criteria for each resilience aspect from the preliminary list:
  - Technical
  - Organisational
  - Social
  - Economic
- Explore the differentiation between *internal* and *external* criteria and their relative importance.

Part 3: Validation of Preliminary Results (±5 minutes)
Participants will be asked to reflect on and validate the initial outcomes. This step serves to confirm whether the identified criteria and patterns align with their professional experience. It also serves as a check to confirm nothing is missed.

Part 4: Requirements for a Resilience Assessment Framework (±15 minutes)

- Discuss requirements to take into account when developing the framework.
- Explore how the proposed framework could be integrated into existing structures or decision-making processes.
- Identify potential challenges for implementation.
- Gather suggestions for improvement or additional elements to include in the final framework.

The interview will conclude with an open question inviting any additional comments or insights from the participant regarding resilience or the framework's practical use.

C.2 Interview Protocol Evaluation

The interviews will last approximately 20 minutes and follow the structure outlined below:

Introduction (±5 minutes)
A short introduction of the researcher and the purpose of the study will be provided. The goal, structure, and expected timeline of the interview will be explained, and informed consent will be confirmed before recording begins.

Part 1: Context and introduction (±5 minutes)

- Explanation of the framework
- Presentation of the list with criteria and inductors.

Part 2: Evaluation input form interviewee (±15 minutes)
Participants will be asked to reflect on and validate the framework

- The way it is designed and developed.
- The construct of the criteria, indicators and description
- The usability for practical use

C.3 Interview summaries Evaluation

Responded 4
The interview strongly validates the proposed resilience framework in terms of novelty, relevance, and practical value. R4 confirms that structuring resilience into criteria supported by measurable indicators represents a meaningful and innovative approach, particularly because the indicators form the operational basis for measurement, reporting, and decision-making.

Design R4 expresses strong appreciation for the overall structure of the framework, particularly highlighting its comprehensiveness beyond the technical domain: *"I'm really interested, probably not so much in your technical one, which I think is done very well, but in the other areas… we hadn't properly considered as being key to resilience. I love the way you've pulled it together. I think it's very comprehensive."*

Graphing the results When discussing the visualisation of the framework through the Venn-type diagram, R4 emphasises its communicative effectiveness: *"That is genius… when you try to explain this using just the spreadsheet or list, they don't get it. What you've shown simplifies it for people. It shows alignment — they are entwined. You can't look at them separately; you have to look at them overall."* According to R4, the graphical representation makes the interdependencies between the resilience domains immediately understandable and therefore significantly enhances the practical usability of the framework.

Practical applicability Regarding organisational usability, R4 confirms that the framework offers a strong and realistic starting point for implementation: *"Starting with a model like this is a great place to start for any organisation… over time you would refine and develop this internally to suit the particular requirements of your own business."* He further explains that the framework supports the identification of high-impact areas and enables prioritisation through the recognition of "low-hanging fruit", allowing organisations to generate value quickly while building maturity over time.

Complexity of the representation Concerning the more detailed representation of criteria, indicators, and their interconnections, R4 acknowledges its complexity but strongly supports its value: *"Yes, it's complex, but it visualises the interactions across the detail side of it… as an organisation, you would want this level of detail of understanding."* He adds that without such mapping, organisations tend to treat resilience dimensions in isolation, whereas the framework explicitly demonstrates their interdependence.

Criteria, indicators, and descriptions Finally, on the formulation of the criteria, indicators, and their descriptions, R4 confirms that the current level of specification is appropriate while still allowing contextual flexibility: *"Every business would take what you've done and change it to suit themselves… giving people this level of indication is the right way to do it because it offers them the flexibility to modify it to suit themselves."*

Responded 7
Design R7 confirms that dividing resilience into multiple aspects and further into criteria and indicators is a sensible and recognisable approach: *"If you're taking a broad look at resilience, it makes sense to have a range of different categories that are prompting thinking across different features."* While R7 notes that further discussion on the detailed formulation and weighting of criteria would be required, the overall structure is considered conceptually sound and useful for systematic reflection.

R7 agrees that organisations with a strong asset management focus may naturally prioritise technical resilience and risk management, potentially overlooking broader organisational and social dimensions: *"It would be easy to focus on the assets and risks and what to do technically and forget about the why... and who needs to be doing what to make sure that if these events happen you can respond and recover well."*

R7 highlights that frameworks such as the "four R's" (risk reduction, readiness, response, recovery) are used in their context to deliberately extend resilience thinking beyond technical performance.

Graphing the results Regarding the graphical representation of the framework, R7 agrees with the premise that resilience is interconnected and non-hierarchical: *"The interconnection is really important."* While R7 agrees with the importance of representing the interconnected nature of resilience, some critical reflection is provided on the effectiveness of this framework. R7 questions whether the Venn-based representation fully captures the true level of interwovenness between resilience domains, noting that visually it may suggest less interrelation than actually exists: *"The circles are visually... it doesn't look super related yet... the Venn diagram alone kind of shows quite a small amount of overlap."*

Practical applicability R7 emphasises the importance of using established external maturity frameworks as starting points for organisational learning: *"There's limited value in everyone doing the same thing separately... having common frameworks that you can point to is really helpful."* Although R7 indicates that the proposed framework in its current form would require further refinement to align with existing industry-standard maturity models, the underlying approach of structured, holistic assessment is strongly supported.

Complexity of the representation R7 observes that more complex network-style diagrams more accurately reflect this interwoven nature, even though such visuals may be harder to interpret quickly. Simpler representations may be more suitable for initial communication, while more detailed diagrams support deeper organisational understanding. R7 further emphasises that the choice of representation should depend on the purpose of the interaction and the intended learning outcome: *"The materials we'd use for those conversations could look quite different depending on what we're trying to learn and understand, what options we're looking at, and what outcome we think we want to go for."* This reinforces the importance of employing multiple complementary visualisations, where simplified representations support initial engagement and communication, while more complex diagrams facilitate deeper analytical understanding and strategic discussion.

D

Resilience and four key principles

D.1 Definition

The definition established for this study is formulated as follows: "The ability of a socio-technical-environmental system to sustain, improve, and innovate its key functions—through absorbing, reacting to, recovering from, adapting to, or reorganising—in response to chronic stresses, abrupt shocks, and disruptions" [39].

Combining this definition with the notion that resilience is characterised and graphed by the two measures of resilience proposed by Adams et al., a more comprehensive understanding of the concept emerges. The two measures of resilience are reduction and recovery. These are based on the 4Rs defined in the section below.

D.2 4Rs Principles

Robustness “Strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function”
Redundancy “The extent to which elements, systems, or other units of analysis exist that are substitutable.”
Resourcefulness “the capacity to identify problems, establish priorities, and mobilise resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis”
Rapidity “the capacity to meet priorities and achieve goals in a timely manner to contain losses and avoid future disruption”
[15]

E

Criteria and Indicators Resilience Framework

E.1 Overview of criteria subdivided by aspects

Table E.1: Criteria subdivided by aspects

ID	Criteria
Technical	
T1	Security
T2	Design for future
T3	Data and digital information
T4	Situational awareness & Testing
T5	Continuous functional service
T6	Crisis respond
Organisational	
O1	Culture
O2	People and competence
O3	Way of working
O4	Coordination with sector
O5	Team Leadership
O6	Strategic orientation
Social	
S1	Expectations and understanding
S2	Communication community
S3	Political & Regulatory Environment
S4	Cooperation & Partnerships
Economical	
E1	Clear financial frameworks
E2	Strategic investments
E3	Cost Distribution

E.2 Full list of criteria and indicators

Table E.2: Resilience criteria with indicators defined and references

ID	Criteria	Indicator	Description	Refs
Technical				
T1	Security			
T1.1		Cybersecurity	Ensuring cybersecurity that detects digital threats in time and wards them off.	A, R4
T1.2		Asset security	Protecting physical assets through secure access, monitoring, and preventive measures.	L, R3–6
T1.3		Physical security	Considering asset security principles to protect critical assets from misuse, loss or manipulation.	L
T2	Design for future			
T2.1		Managing network	Actively managing and future-proofing the network through monitoring, planning, and control.	B
T2.2		Backup systems	Implementing backup facilities that guarantee continuity in the event of malfunctions, and testing them regularly.	C, R3
T2.3		Redundancy N-1	Implementing N-1 redundancy to ensure the system remains functional when one component fails.	R4–6
T2.4		Design to be resilient	Designing the system so it incorporates resilience principles from the design phase onwards (e.g. flood risk, scalable capacity, and future requirements). Balancing between oversizing and recovery capacity is key.	A
T2.5		Renewable integration	Actively exploring what is needed to integrate renewable energy sources in a way that ensures stability and reliability.	R4, 6
T2.6		Capacity and demand growth	Planning capacity expansion and anticipating future growth in supply and demand.	A R1, 2, 4, 5
T3	Data and digital information			
T3.1		Documentation-data standardisation	Complete and accessible documentation on systems, processes and assets. Standardisation of the data to ensure consistency, comparability and quality.	A, R1–2
T3.2		Asset data quality	Ensuring reliable data and technical information through validation, and updating. Measuring is knowing, when you know what you are measuring.	A, B
T3.3		Data-driven planning	Support decision-making with up-to-date and reliable information by creating accurate data using data-driven planning.	A, B
T3.4		AI application	Consider applying AI and analytical methods to predict patterns, risks, and future needs.	A, R4–5
T3.5		Data transparency and sharing	Creating transparency in data so that interests and risks can be properly interpreted. Sharing relevant findings within the organisation and cross-sectionally to increase joint situational awareness.	B, D, R1
T4	Situational awareness & testing			
T4.1		Scenarios and simulations	Identify vulnerabilities through scenarios and simulations to assess system responses under stress conditions.	A, B, R3–6

Continued on next page

ID	Criteria	Indicator	Description	Refs
T4.2		Risk assessment	Conducting risk analyses to identify vulnerabilities and assess the likelihood of disruptions.	D, E, I, R1, 3, 6
T4.3		Impact assessment	Conducting impact assessments to evaluate the consequences of potential disruptions.	R3–6
T4.4		Identification of condition	Performing systematic condition identification to detect degradation and emerging risks.	F, R4
T4.5		Vegetation resistance	Identify potential hazards to the functioning of assets caused by surrounding vegetation.	B, R5
T5	Continuous functional service			
T5.1		Asset prioritisation strategy	Applying an asset prioritisation strategy to determine which assets are critical for maintaining service continuity.	B, E, I, R4
T5.2		Effective asset management	Integrated asset management strategy, including maintenance, monitoring, and lifecycle planning.	I, R4
T5.3		Management of resources	Efficient management and balancing of resources to ensure continuity of operations during disruptions.	F, R3, 4,
T5.4		Understanding and managing disruptions	Understanding and managing disruptions through proactive planning and adaptive response strategies.	R3, 5, 6
T6	Crisis respond			
T6.1		Actions to secure	Identify actions that need to be taken in order to be able to act in the disruption events (e.g. provision of paper information, own radio systems).	R3
T6.2		Logistics	Optimising logistics processes so that materials, parts and resources are available on time for operational continuity.	A, R3
T6.3		Supply chain	Managing the supply chain to control delivery reliability, stock levels and dependencies.	A, R3, 6
T6.4		Spare parts	Know where your spare parts are and how they can be utilised.	C, R3
T6.5		Recovery action	Cross-sector, integrated, flexible, tested and collaborative mechanisms to provide short- medium- and long-term recovery of the system.	B, K, R3
Organisational				
O1	Culture			
O1.1		Organisation community	Encouraging a strong and connected community within the organisation.	A, I, R1–6
O1.2		Innovation focus	A predisposition to explore alternative ways to tackle challenges and respond to the unexpected.	A, F, K
O1.3		Mission and values	Clear and distinct mission and vision, understood and supported by the community.	D, I
O1.4		People orientation	Encourage an environment in your organisation where the workforce feels comfortable sharing, and is involved	F
O2	People and competence			
O2.1		Community	Same as O1.1	A, R1–6
O2.2		Skills and abilities	Ensuring that employees are sufficiently trained to independently perform complex tasks.	A, I, R1–6

Continued on next page

ID	Criteria	Indicator	Description	Refs
O2.3		Learning	Facilitating continuous learning by encouraging professional growth and development.	A
O2.4		Motivate people	People are most motivated when they have autonomy over their work, the opportunity to master skills, and a sense of purpose are most motivated when they have autonomy over their	G
O2.5		Workforce engagement	Proactive initiatives to promote workforce engagement.	A, F, R6
O3	Way of working			
O3.1		Flexible for change	Applying an agile way of working to respond flexibly to changes and disruptions.	A, I
O3.2		Evolving / change way of working	being ambidextrous: exploiting knowledge to improve efficiency while exploring knowledge to innovate and so gain competitive advantage.	R2, 3
O3.3		Lessons learned and best practice	Mechanisms in place for identifying and communicating energy resilience best practice.	N, R4
O3.4		Process standardisation	Standardise processes to promote consistency, quality and efficiency.	A, R1, 4, 5
O3.5		Continuous improvement	Ensure that the organisation continues to learn, monitor what you are doing, evaluate the effect and, most importantly, communicate and promote what works in order to continue learning.	H, I
O3.6		Knowledge management	Organisations focus on improving the ways in which they create, capture/store, distribute/-transfer and effectively use/apply knowledge.	G, F
O4	Coordination with sector			
O4.1		Identify coherence	Identify and promote coherence between internal and sector-wide resilience initiatives, find spillover effects to other sectors.	R2, 5
O4.2		Coordination with sector	Actively maintaining cooperation with sector parties to increase joint capacity and knowledge, before, during and after disruptions.	D, J
O4.3		Aligning common goals	To provide clarity across the industry about priorities and guidance on prioritising investment.	F, J
O4.4		Establishing trust	A certain degree of trust is necessary for collaboration. Trust is a two-way street, ensure this is achieved in order to share best practices and data, for example.	R1, 2, 6
O4.5		Resilience ownership	Identifying and communicating the roles, responsibilities and interfaces among energy stakeholders – including responsibility for providing resilience to a system with a focus on protecting.	A, K
O5	Team leadership			
O5.1		Leadership	Leadership is defined as the process by which an individual influences others in ways that help attain group or organisational goals	A, D
O5.2		Rapid decision-making	Organisations must be equipped to make quick deliberate decisions in the event of a disruption. Agreements on this must be made in advance.	A, J, R3
O5.3		Lines of control	Clarification of lines of control so that responsibilities are clear (during disruptions).	J
O5.4		Collaboration	Promoting cooperation between departments and stakeholders at leadership level.	R1

Continued on next page

ID	Criteria	Indicator	Description	Refs
O5.5		Clear and realistic target	Setting clear and realistic goals that contribute to a resilient organisation. Implementation only works if people recognise the benefits and believe it is achievable.	H
O5.6		Responsibilities defined	Explicitly defining responsibilities to ensure ownership and accountability.	D
O5.7		Communication / leadership	Effectively communicating strategies, decisions and expectations at all levels.	F R1–4
O6	Strategic orientation			
O6.1		Aligning goals	Aligning organisation-wide goals with resilience ambitions.	B, R1, 4
O6.2		Multi-timescale oriented	Adopt a short-term and long-term focus in investments, planning and decision-making for the expected evolution of the energy sector. Regularly reassess whether the focus needs to be adjusted.	A
O6.3		Shared vision	Work on developing a shared vision of resilience that is supported by all levels of the organisation.	D, J
O6.4		Plans in place	Are there plans in place? This includes drawing up concrete plans that specify who is responsible for the different elements of disaster response and recovery plans	J, R3, 4
O6.5		Understanding current market	Mapping the current market and external environment in order to identify future challenges at an early stage.	B
O6.6		All-of-business mindset	Building resilience is an all-of-business effort involving every corporate function	R4
O6.7		Approach to resilience	Implement a clear approach to resilience that guides actions, priorities, and responsibilities.	R5
Social				
S1	Expectations and understanding			
S1.1		Public understanding	Designing mechanisms to increase public understanding of risks, disruptions, and the organisation's role in ensuring energy or service security.	B, R1–3
S1.2		Managing stakeholders' expectations	Actively managing the expectations, informing and preparing customers, businesses and stakeholders in advance for possible scenarios or emergencies so that they understand what is possible during disruptions.	R1
S1.3		Reputation	Acknowledging and understanding that reputation is strongly linked to expectations management	R1, 3, 5
S2	Communication community			
S2.1		Clear communication	Define and implement mechanisms for effective communication with customers. Providing clear, consistent and transparent communication to all relevant target groups.	A, I
S2.2		Media communication	The media is particularly important during a disruption. Be prepared by identifying your media contacts and developing protocols for what information will be shared.	R3
S2.3		Community engagement	Actively engaging communities in energy issues and creating understanding of what measures you take to improve resilience.	B, D, R1–6

Continued on next page

ID	Criteria	Indicator	Description	Refs
S2.4		Responsibility function	Define and develop social responsibility tasks, for example, taking into account what exactly is behind the connection.	B, R1, 4, 5
S2.5		Encouraging energy efficiency	Promoting energy, demand and consumption efficiency among customers through campaigns and awareness programmes.	K
S3	Political & Regulatory Environment			
S3.1		Regulator	Fostering constructive relationships with regulators to achieve shared resilience goals.	R1, 3, 4
S3.2		Legislation and regulating	Compliance with and active application of relevant laws and regulations	A, I
S3.3		Geopolitical landscape	Understanding geopolitical developments and international dependencies that may influence the organisation and business operations.	A
S3.4		Government	Collaborate closely with local, national and (European) authorities to support a coordinated resilience approach and accelerate processes.	R3, 4
S4	Cooperation & Partnerships			
S4.1		Collaboration with organisations	Establishing structural partnerships with organisations within and outside the sector to strengthen resilience.	R1, 4, 6
S4.2		Data sharing	Sharing relevant data and information between partners to improve joint insights and response speed.	J, R1
S4.3		Spillover effects	Understanding and managing spillover effects through interconnection between organisations, systems or infrastructures.	R2
S4.5		Stakeholders compliance	Actively maintaining effective partnerships that contribute to operational and strategic reliability.	F
S4.6		Long-term contracts and relationships	Establishing long-term contracts and relationships that increase stability and predictability within the chain.	A
Economic				
E1	Clear financial frameworks			
E1.1		Financial plan adherence	Ensuring that operational expenditure (opex) structurally takes into account the financial requirements for resilience solutions (Cost-benefit analysis).	A
E1.2		Financial insights	Analysing the financial consequences of unexpected shocks or stressful situations for the organisation.	R6
E2	Strategic investments			
E2.1		Investment prioritisation	Systematically prioritising investments based on risk, impact and strategic importance for resilience.	A, R3
E2.2		Investment planning	Developing detailed investment plans that take into account future uncertainties and capacity requirements.	A, R4, 5
E2.3		Special investment criteria	Apply specific investment criteria that support resilience, reliability and sustainability.	K
E2.4		Informed investments	Establishing transparent financial frameworks that indicate how resilience investments are planned, prioritised and accounted for based on data.	E, K

Continued on next page

ID	Criteria	Indicator	Description	Refs
E2.5		Renewable capacity insurance	Defining strategy to protect energy investing in renewable capacity to increase the robustness of the energy system.	R4
E3	Cost distribution			
E3.1		Who pays for resilience	Work on agreements to determine who is responsible for the costs of resilience: the government, customers, shareholders or the organisation itself.	A
E3.2		Affordable / economic sustainable	Developing a sustainable financing strategy for resilience measures within the organisation.	R6
E3.3		Cost of adoption	Analyse the costs of modifications, upgrades and mitigation measures in order to provide insight into the total costs of resilience.	M

Reference key: A: Observations ITAMS; B: Roege et al. [59]; C: Ampratwum et al. [5]; D: Twigg [68]; E: Bie et al. [12]; F: Sapeciay et al. [61]; G: Newell et al. [51] H: Gremyr et al. [33]; I: Asset Management [9]; J: Cantelmi et al. [17]; K: ARUP [8]; L: Dutch legislation [71] M: Ricciardi et al. [58] N: Mitchell et al. [48] R: Interview respondents (R1 to R6)

F

Enlarged View of Framework Figures

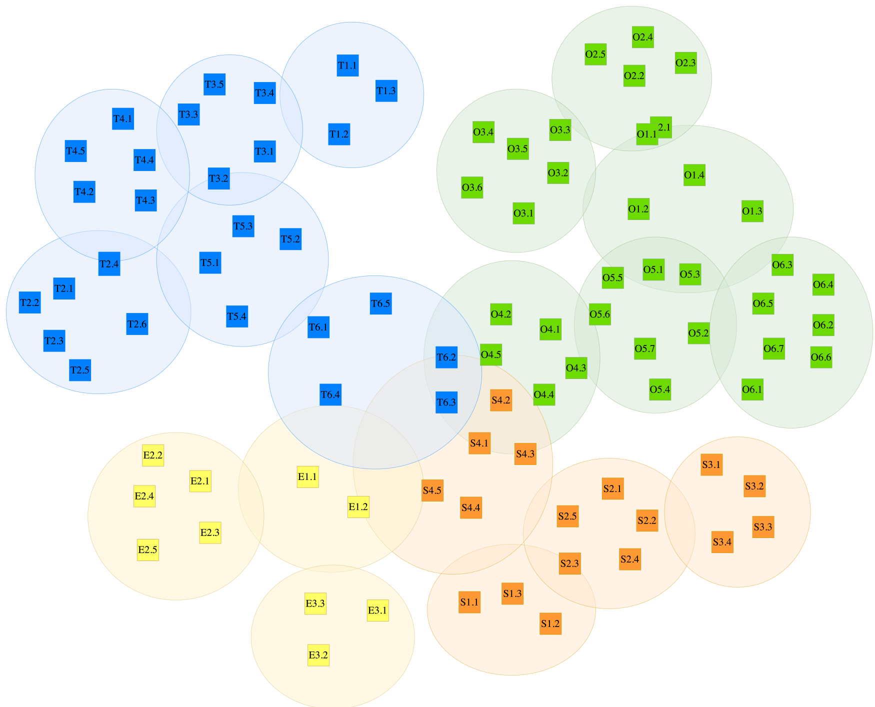


Figure F.1: Enlarged view of framework figure 4.6a presented in Section 4.3

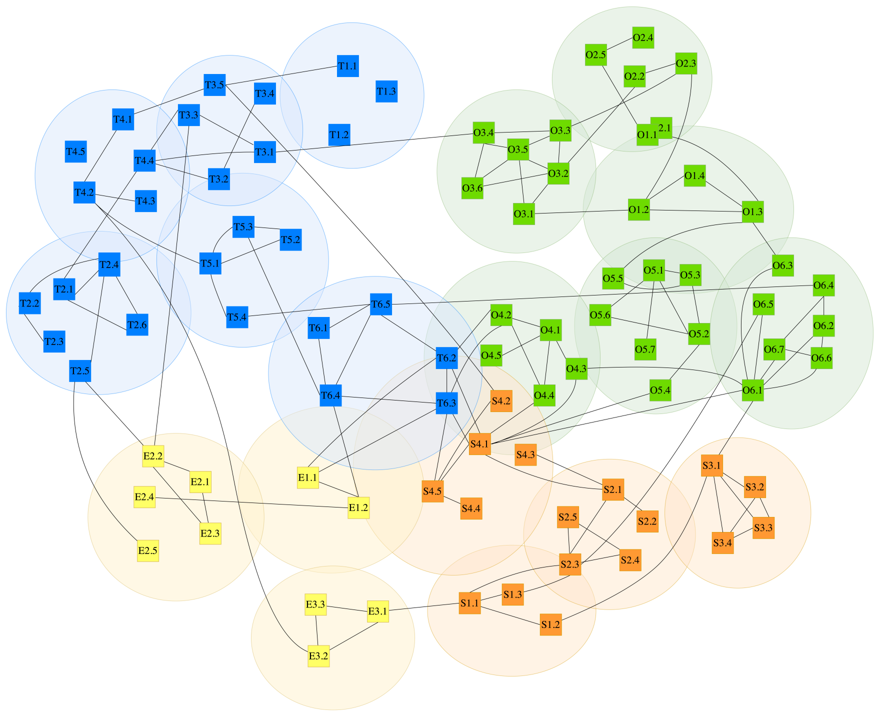


Figure F.2: Enlarged view of the framework figure 4.6b presented in Section 4.3

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“When I am working on a problem, I never think about beauty........
but when I have finished, if the solution is not beautiful, I know it is wrong.”

— *R. Buckminster Fuller*

Resilience Beyond Technical Systems

Designing a framework for assessing resilience in the energy sector