Integrating Energy Policy and Climate Solutions

A Strategic Framework for Underground Hydrogen Storage in Salt Caverns

SEN2331: CoSEM Master Thesis

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by

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Project Duration:	May 2024–September 2024
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Preface

Over the years, my interests have increasingly focused on renewable energy, climate change, and policymaking. These passions were solidified through my academic studies, and two internships, where I deepened my understanding of these topics. When I began searching for a thesis topic in September 2023, I was determined to find one that combined these interests. After careful consideration, I chose a topic that embodies this intersection, leading to the thesis before you. This work reflects both my academic journey and my commitment to addressing the challenges of sustainable energy and climate policy.

Embarking on this master's thesis journey was initially daunting, especially after my challenging bachelor's thesis experience, which took place in an uninspiring basement laboratory during the COVID-19 pandemic. However, this current experience has proven to be transformative.

Collaborating with Amineh Ghorbani, Renske van 't Veer, and Zofia Lukszo has been incredibly enriching. I have had the privilege to work alongside three inspiring women who excel in their fields. Their collaborative sprit and positive communication motivated me to strive for excellence.

I am grateful to my first supervisor, Amineh, for her guidance and support throughout this process. Zofia, your infectious enthusiasm and methodical approach were uplifting. I would also like to thank Renske, her invaluable assistance in refining my thesis cannot be overstated. Your readiness for discussions, quick availability, and insightful feedback were instrumental in shaping my work. The passion of each of you for my thesis subject made our meetings both enjoyable and productive.

With the completion of this thesis, my academic journey, which began at the University of Groningen and continued at the Technical University of Delft, comes to an end. I am excited to continue my journey and begin my professional career. Perhaps in the future, inspired by my father's example, I might pursue further studies, as I have always enjoyed learning.

Christine Zwaan
Delft, September 2024

Summary

Green hydrogen is emerging as a critical component in the global fight against climate change, offering a viable pathway to reduce greenhouse gas (GHG) emissions and facilitate the transition to a low-carbon economy. As renewable energy sources (RES) like wind and solar become more prevalent, the challenge of their variable supply and the resulting green hydrogen production, demands robust energy storage solutions to ensure stability and flexibility in the energy supply. Underground hydrogen storage (UHS) in salt caverns has been technically proven as an efficient and effective method to address these challenges. However, despite the growing need for UHS, the development of such projects is lagging behind.

The behaviour of actors involved in UHS project is guided by formal rules, known as institutional statements. While existing research on UHS salt caverns has predominantly focused on technical aspects such as safety, efficiency and injection methods, the formal institutional dimension remains unexplored. This dimension, which emphasizes the connectivity and interdependency between rules and regulations, is crucial for understanding how rules shape the development of UHS projects.

The primary goal of this research was to systematically analyse the institutional network characteristics and relationships between formal institutions within the context of UHS in salt cavern development in the Netherlands. To achieve this, an extended methodology was devised, focusing exclusively on the formal institutional environment. In doing so, the research aimed to formulate policy recommendations for policymakers based on insights derived from the institutional analysis related to connections, interdependencies, and key characteristics. Ultimately, the research sought to answer the following main research question:

How does the institutional framework in the Netherlands impact the development of underground hydrogen storage projects in salt caverns?

Research framework

To answer this research question, the study is grounded in institutional theory, particularly focusing on the role of formal institutions in shaping the development of UHS in salt caverns. The research draws on the Institutional Analysis and Development (IAD) framework and Institutional Grammar 2.0 (IG 2.0) syntax to dissect the institutional environment. The IAD framework provides a structured approach to analysing the rules that govern decision-making processes, while IG 2.0 offers a detailed syntax for coding and analysing institutional statements. By integrating these tools, the study offers a comprehensive analysis of the formal rules, regulations, and institutional relations that govern UHS development.

Methodology

The study applied and extended the Institutional Network Analysis (INA) method to the case study of UHS in salt caverns in the Netherlands. The INA method is designed to identify institutional relations and analyse how formal and informal institutions interact within an institutional environment. In this research, the method was modified to focus exclusively on formal institutions, excluding informal institutions. Two extensions were made to deepen the analysis. First, a rule typology analysis was added to analyse the key characteristics of the formal rules within the institutional environment. Second, the approach was further refined by categorizing drivers behind institutional connections.

Additionally, the research also standardized and refined the formalization process of institutions, using a standardized template to enhance consistency and transparency. Each institutional statement derived from policy documents was logged with the corresponding document and article number, improving traceability.

Three key action arenas were identified in the research: (i) project initiation, (ii) community and stakeholder engagement, and (iii) closure, safety, and subsidence control. For each of these action arenas,

an Institutional Network Diagram (IND) was constructed to visualize the relations and dynamics within the institutional framework.

Key findings

The application of the extended INA methodology uncovered several critical insights into the institutional environment governing UHS in salt caverns.

First, the study identified a misalignment between the Dutch government's policy intentions, as outlined in the Subsurface Spatial Planning Vision, and the actual practices dictated by the Environment and Planning Act. While the Act emphasizes participation and the opportunity for third parties to propose solutions, the Vision often rules out these possibilities by pre-determining the most fitting solution for a specific problem.

Second, the analysis revealed an institutional void, particularly in the area of participatory governance. Although several formal institutions advocate for a participatory approach, the policy documents lack clear guidelines on how third parties should be included in decision-making processes and how the effectiveness of participation strategies should be assessed.

Next, the study highlighted the central role of specific actors, such as the competent authority and project developers, who hold significant influence within the institutional network. Additionally, several objects related to permit applications and operational procedures were identified as potential bottlenecks due to their high embeddedness scores.

Lastly, the analysis of the rule typology revealed that boundary, information, and position rules are the most prevalent within the institutional context. This suggests that the institutional environment is heavily focused on regulating access and exit within the context and ensuring the dissemination of information to relevant stakeholders.

Recommendations

Based on the analysis and insights, the research offers several key recommendations for improving the institutional environment.

First, it is recommended that UHS projects be anchored not only in the national visions, but also in local energy policies and environmental plans. Facilitating discussions between national and local representatives can help align participation expectations and enhance stakeholder engagement.

Second, policymakers should provide additional guidance in the form of guidelines, templates, and consulting resources to enhance the quality of participation strategies and ensure that third-party involvement is meaningful and effective.

Finally, the study also outlines several areas for future research. First, exploring the interplay between formal and informal institutions could provide a more comprehensive overview of the institutional network. Additionally, cross-validation of the research steps by multiple researchers is recommended to enhance the robustness of the findings. Lastly, incorporating modelling tools could help study the institutional dynamics of project development and policymaking more effectively.

Thus, all in all, this research provides a detailed analysis of the formal institutional environment impacting the development of UHS in salt caverns in the Netherlands. By identifying institutional conflicts, voids, and key actors, the study offers valuable insights that can inform policy formulation and strategic planning for UHS projects. However, further research is needed to validate these findings and explore the broader implications of the institutional framework of UHS developments.

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Abbreviations

ABDICO	Attribute, Object, Deontic, Aim, Condition, Or else
IAD	Institutional Analysis and Development
IG 2.0	Institutional Grammar 2.0
INA	Institutional Network Analysis
IND	Institutional Network Diagram
SRA	Seismic Risk Analysis
SoDM	State Supervision of Mines (Staatstoezicht op de Mijnen)
UHS	Underground Hydrogen Storage

1 Introduction

In 2019, the Urgenda Foundation achieved a landmark legal victory in the Netherlands with the case State of the Netherlands vs. Urgenda Foundation. Initiated in 2013, this case involved the foundation, representing 886 Dutch citizens, suing the government to establish a legal obligation for reducing greenhouse gas (GHG) emissions and combating climate change ("Urgenda Foundation", 2019). This groundbreaking lawsuit underscores the increasing societal demand for sustainability in response to the visible impacts of climate change worldwide.

Global energy demand has surged due to population growth. According to the International Energy Outlook, the global economy is projected to grow at an average rate of 2.6% per year until 2050 (Heymi et al., 2023), while the global population is expected to increase from 8 billion today to nearly 10 billion by 2050. Meeting this growing energy demand presents a significant challenge, adding pressure to the global energy system (European Commission, 2024). Furthermore, climate change effects are becoming more widespread and frequent. Human activities, through GHG emissions, have unequivocally caused global warming and its associated adverse effects (Calvin et al., 2023). The Intergovernmental Panel on Climate Change (IPCC) emphasized in its 2018 report, "Global Warming of 1.5 Degrees," the urgent need to reduce GHG emissions more rapidly and at a faster pace than previously considered (IPCC, 2018).

Recently, the Dutch government has increasingly recognized the potential of green hydrogen to enhance sustainability across various industries (Ministerie van Economische Zaken en Klimaat, 2024). Green hydrogen, produced through the electrolysis of water using renewable electricity, is carbon dioxide-free (Elzenga & Strengers, 2024). This growing awareness has led to the initiation of several electrolysis projects in the Netherlands, with seven major initiatives receiving government funding (Ministerie van Economische Zaken En Klimaat, 2022). Green hydrogen is particularly attractive for the Dutch energy system due to the country's abundant renewable resources, especially offshore wind, which can be used to produce hydrogen via electrolysis (Gigler et al., 2021). Moreover, green hydrogen can significantly cut emissions from carbon-intensive industries such as chemicals, steel, and refining, and offers solutions for energy storage and grid stability. Additionally, the extensive natural gas infrastructure can be adapted for hydrogen transport, facilitating a cost-effective transition. The Netherlands is also strategically positioned at the centre of the European hydrogen infrastructure proposed by 11 European grid operators (Gigler et al., 2021).

The Dutch government aims to achieve 500 megawatts of electrolysis capacity by 2025 and 3 to 4 gigawatts by 2030, with plans for hydrogen storage and infrastructure expansion (Elzenga & Strengers, 2024). However, this ambitious goal is contingent upon the rapid development of renewable electricity sources. As stated by the Ministry of Economic Affairs and Climate Policy in a parliamentary communication in June 2023, reaching 4 gigawatts of electrolysis capacity by 2030 is already highly ambitious. By 2032, the government aims for an electrolysis capacity of 8 gigawatts, depending on the pace of renewable energy advancements, infrastructure expansion, and electrification trends among industrial end-users (Ministerie van Economische Zaken en Klimaat, 2023).

However, the future is uncertain, which is particularly true for the energy transition. When it comes to the application of hydrogen, uncertainties seem to compound. It is not merely the question of when and how much hydrogen will be available, considering the concurrent demand from various sectors in the industry. There is also the uncertainty regarding current regulations, regarding their complexity, clarity and alignment, added to this is the uncertainty regarding potential revisions, timelines, and changes (Nauta & Geilenkirchen, 2021). In light of these challenges, the development of the hydrogen infrastructure is lagging behind and targets set by the Dutch government seem to become even more ambitious (Gigler et al., 2021).

1.1. Focus of this research

The production, transport, and use of large volumes of hydrogen depend on infrastructure such as pipelines, ships, terminals, and scheduled deliveries, which are often influenced by fluctuating production levels. As hydrogen demand grows in the Netherlands, storage becomes increasingly important to offer the flexibility needed to match supply with demand (Nationaal Waterstof Programma, 2022). Storage is critical for ensuring supply security and enhancing both the stability and flexibility of an energy system increasingly reliant on variable production sources (van der Linde, 2022). Here, stability refers to the ability to respond to short-term fluctuations, while flexibility pertains to managing supply variations on a seasonal scale (Groenenberg et al., 2020).

Currently, underground hydrogen storage (UHS) in salt caverns stands out as one of the most promising solutions for long-term storage. This is due to several advantages, including high withdrawal capacity, enhanced safety, and relatively low creation costs (Coarita-Tintaya et al., 2023; Tackie-Otoo & Haq, 2024). Salt caverns are created through a process called solution mining, or leaching, which involves injecting water into a cavern to dissolve the salt and then extracting the resulting brine through a single well. The same well is later used for both hydrogen injection and withdrawal (Tackie-Otoo & Haq, 2024).

Research indicates that by 2030, a minimum of three to four salt caverns with a combined storage capacity of 750 to 1,000 gigawatt-hours (GWh) will be required to meet demand (Nationaal Waterstof Programma, 2022). Beyond 2030, the need for storage may increase to dozens of caverns (van Gessel et al., 2022). Globally, only four large-scale hydrogen storage facilities in salt caverns are operational, but experience from these sites shows that hydrogen can be stored safely over extended periods. In the Netherlands, the technical potential for hydrogen storage is especially large, estimated at 43.3 terawatt-hours (TWh) (Groenenberg et al., 2020).

Despite the Dutch government's recognition of the importance of hydrogen infrastructure, uncertainty persists regarding future hydrogen prices, infrastructure development timelines, technological advancements, and government support. These uncertainties have slowed adoption and development efforts (Groenenberg et al., 2020). The interdependency between hydrogen infrastructure availability and demand for hydrogen-based technologies creates a "chicken-and-egg" problem. Without robust hydrogen infrastructure, including large-scale storage, potential users hesitate to adopt hydrogen technologies, as stable and flexible supply cannot be guaranteed. Conversely, without sufficient demand for hydrogen technologies, companies are reluctant to invest in large-scale storage facilities. This feedback cycle hinders the overall progress of the hydrogen industry (Gigler et al., 2021).

1.2. Case specification: Zuidwending

In the northern Netherlands, beneath Zuidwending in Groningen, a substantial salt formation, comparable in size to Mont Blanc, has been identified (HyStock, 2024). Through drilling and leaching, large salt caverns have been created, most of which are currently used for natural gas storage. In 2020, EnergyStock launched the Zuidwending hydrogen storage project, aiming to store hydrogen in these caverns similarly to how natural gas is stored (Gasunie, 2024). Plans are underway for the construction of four new salt caverns specifically for hydrogen storage at the Zuidwending site. Additionally, an above-ground facility will be established to manage hydrogen injection and extraction. The six caverns currently used for natural gas storage will be retrofitted for hydrogen storage in the future (Gasunie, 2024).

The exploitation of the salt caverns involves various stakeholders working together: EnergyStock, Nobian, Hystock, and Gasunie (Gasunie, 2024). The storage facility will eventually connect to the hydrogen backbone, allowing hydrogen to be stored for weeks or months, which not only supports sustainability but also enhances the flexibility and stability of an energy system with a significant share of renewables (HyStock, 2024).

1.3. Identification of the knowledge gap

1.3.1. Literature review

Technology developments

In recent years, UHS in salt caverns in the Netherlands has been extensively studied. The scientific community has made significant progress in understanding the technical intricacies surrounding hydrogen storage, particularly in the context of the Netherlands' geological landscape (Elzenga & Strengers, 2024; van Gessel et al., 2021). Extensive geological assessments have evaluated the suitability of Dutch salt formations for large-scale hydrogen storage. Studies by Juez-Larré et al. (2023), Groenenberg et al. (2020), and AbuAisha and Billiotte (2021) have analysed the porosity, permeability, and structural stability of salt caverns, providing valuable insights into their capacity and integrity as storage reservoirs. Moreover, Malachowska et al. (2022) assessed the potential of UHS in salt caverns, considering both safety and economics. The study found that salt caverns offer protection against external influences (e.g., fire, military actions), provide high storage pressure for optimal energy density, require limited surface area, and have lower investment costs compared to surface storage alternatives. These geological assessments have been complemented by engineering analyses aimed at optimizing storage operations.

Schrotenboer et al. (2022) explored advanced injection and withdrawal operations, proposing innovative approaches to minimize environmental impacts, improve storage efficiency, and ensure operational safety. Furthermore, numerical modelling and simulation efforts led by researchers such as Coarita-Tintaya et al. (2023) have enhanced the understanding of salt cavern behaviour under various operating conditions, guiding the design and optimization of UHS facilities. Lastly, geochemical and microbial risks related to salt caverns have been explored by Dopffel et al. (2021) and Aftab et al. (2022), contributing to risk mitigation strategies.

Through interdisciplinary collaboration, the technical feasibility of hydrogen storage in salt caverns has been significantly advanced. These findings suggest that using salt caverns for hydrogen storage does not compromise cavern stability or promote hydrogen losses during long-term storage. This underscores the high potential of this technology and lays a solid foundation for further development and implementation.

Institutional dimension

Beyond the technical aspects, the successful implementation of energy storage projects, including UHS in salt caverns, crucially depends on the regulatory and institutional frameworks governing these projects (NAM, 2022; Remmelts & Cino, 2019). The literature highlights the complexity of current regulations, the lack of clarity, and, in some cases, a misalignment of policies. Additionally, uncertainties surrounding potential regulatory revisions and the timing of such changes create further challenges. The slow pace of permitting and the short timeframes for business cases also present significant obstacles (Remmelts & Cino, 2019; van Zoelen, 2024). The initial implementation stages of hydrogen storage projects, characterized by significant upfront costs and uncertain returns, highlight the critical need for supportive regulatory policies (Hasankhani et al., 2023).

Institutions, defined as the explicit and tacit rules, norms, and strategies that inform actors on what actions they can or must take in certain situations, play a crucial role in shaping the energy landscape (Polski & Ostrom, 1999). They comprise formal institutions, set by legislators through laws and agreements, and informal institutions, which include social practices, norms, and professional codes (Roggero et al., 2018). These mechanisms regulate infrastructure development, information exchange, and decision-making processes. Thus, understanding institutional frameworks is essential for informing more effective policy (Frantz & Siddiki, 2021).

Insights from other energy storage sectors, such as pumped hydro energy storage (PHES), underscore the importance of robust governance structures. In Switzerland, the regulatory framework governing PHES has been examined, with researchers like Ali et al. (2021) and Crettenand (2021) identifying policy instruments designed to support development. Crettenand (2021) noted that while PHES is accommodated within Switzerland's institutional framework, it faces barriers due to intersecting legislation (e.g., environmental, water, and energy laws) and administrative burdens. These findings provide policymakers with actionable insights to streamline regulatory processes and enhance institutional support for PHES development (Ali et al., 2021). This research highlights the critical role that regulatory and institutional frameworks play in advancing the adoption of new energy storage technologies.

1.3.2. Knowledge gap

Hydrogen long-term storage developments are essential to meet increasingly pressing and legally binding emission reduction targets (Nationaal Waterstof Programma, 2022). While the technical feasibility and potential of hydrogen storage in salt caverns have been extensively researched, the institutional dimension is equally crucial for the scale-up and roll-out of large infrastructure networks (Hasankhani et al., 2024; Odenweller et al., 2022).

Institutional frameworks encompass the rules, norms, and strategies established by governmental and regulatory bodies, directly influencing project approval, development, and operation (Congleton & Ostrom, 2007). For UHS in salt caverns, these frameworks define legal requirements for licences and permits, environmental standards, and stakeholder engagement. A clear understanding of the institutional framework is key for ensuring regulatory compliance, fostering stakeholder engagement, and achieving societal acceptance.

However, research on the institutional rules governing UHS in salt caverns in the Netherlands remains limited. There is a lack of comprehensive knowledge about the specific institutional rules shaping the development of storage infrastructure. Given the long lead times for developing underground storage facilities and the potential legal challenges, delays, or community opposition, it is critical to gain insights into the institutional dimension now. This will support the timely development of salt caverns and contribute to providing stability and flexibility in the energy market.

1.4. Research method

1.4.1. Research questions

To address the identified knowledge gap, the main research question is articulated as follows:

How does the institutional framework impact the development of underground hydrogen storage projects in salt caverns in the Netherlands?

To delve deeper into the research question, the following sub-questions are devised:

1. How can the institutional environment for UHS in salt caverns be systematically represented and analysed?
2. How does the institutional environment inform the assessment of project development efforts for UHS in salt caverns?
3. What are the key characteristics of the institutional environment surrounding UHS in salt caverns?
4. What analytical insights are derived to understand and potentially enhance the institutional environment of UHS in salt caverns?

The research (sub-)questions aim to provide a comprehensive understanding of the regulatory landscape's impact on hydrogen storage development, while aiming to offer insights for improving adaptation efforts.

1.4.2. Approach

This research focuses on a specific niche within the hydrogen industry and infrastructure: UHS in salt caverns. By examining the relationships between institutions within this context, the study employs a qualitative and quantitative approach to explore the institutional environment governing UHS developments. The following section outlines the sub-questions and the approach used to address them.

Sub-question 1 centres on developing the methodology used throughout the study. Extensive desk research is conducted to review potential methodologies that align with the research objectives. The selection of methods is guided by their relevance to the main research question, which necessitates a thorough understanding of institutional concepts relevant to the study.

Once the methodology is established, *sub-question 2* focuses on assessing the institutional environment. Building on the theoretical concepts, the study adopts a qualitative and quantitative approach to analyse institutional structures. Desk research is conducted to identify suitable analytical methods for this purpose. The qualitative analysis seeks to identify institutional voids, bottlenecks, challenges, and overlaps that could affect UHS project developments. Meanwhile, the quantitative analysis employs network metrics to evaluate the institutional networks, providing deeper insights into the relationships and dynamics that may not be evident through network visualization alone.

Sub-question 3 shifts focus to the key characteristics of the institutional environment, derived from the previous assessments. This question involves rule typology analysis, offering insights into the nature of institutional statements. This coding process uncovers patterns and structures within the institutional environment, emphasizing areas where rules are most influential.

Finally, *sub-question 4* synthesizes the insights gained from the analysis and proposes recommendations to improve the institutional framework governing UHS in the Netherlands. The findings from the previous analyses are used to draw conclusions about the effectiveness of current institutional arrangements and suggest ways to enhance policy and regulatory frameworks.

1.5. Relevance

1.5.1. Societal relevance

The importance of decarbonizing industries and improving sustainability to combat climate change, has grown tremendously in recent years and will become even more critical in the future. Green molecules, and especially green hydrogen, will prove to be important if climate change targets are to be met. However, there remains little insight into how the current institutional environment influences the green hydrogen transition, especially considering storage in salt caverns. This research aims to provide insight into the institutional interactions and dependencies that govern the development of hydrogen storage in salt caverns, in order to prevent unsystematic and individualistic approaches by companies. In doing so, the research provides a framework for improving the support and development of hydrogen storage in salt caverns, to facilitate flexibility and stability of the future energy system.

1.5.2. Scientific relevance

Systematic research into the relation between institutions, and thereby identifying and mapping the networks, holds significant scientific relevance in the pursuit of a green hydrogen transition in the Netherlands. Understanding and visualizing the institutional network is paramount for informed decision-making and institutional support, as it visualizes the gaps and barriers to the adoption of hydrogen storage in salt caverns. The current body of academic literature is highly technically oriented, as described in section 1.3. Research into the institutions and regulations governing the adoption remains limited, which underscores the scientific relevance of the thesis project.

1.5.3. MSc program

There are several ways why the thesis subject relates well will the contents and requirements of the Master Complex Systems Engineering and Management. Firstly, it is argued that the research concerns a complex system due to the following aspects: (i) both the behaviour of actors and the technological components play an important role; (ii) the interaction of various important actors ensure the context relates to a multi-actor system; (iii) both public and private actors are involved in the system; and (iv) there is not one obvious solution to the described problem (Koppenjan & Groenewegen, 2005). Secondly, the research topic concerns the energy transition, which is often described as a large complex sociotechnical system (Verbon & Geels, 2007). Where a sociotechnical system is defined as a system which contains both physical-technical elements, and networks of independent actors (de Bruijn & Herder, 2009). Therefore, as this research study relates both to a complex system, and a sociotechnical system, it aligns well with the objective and requirements of the master program.

1.6. Structure of the research study

In Figure 1.1, the research flow diagram is shown. The diagram shows a visual representation of the research design. Per chapter, the input, research flow and output are given. The input relates to the research methods used to answer the sub-questions. The per section output are used as input for the following chapter. As a whole, the research flow diagram aims to answer the main research question.

Chapter 2 will delve into key concepts which provide the foundation for the research, focussing on institutions, their relations, network metrics, and offering a conceptual framework for analysis. Chapter 3 outlines the research methodology and details the steps for applying the selected INA method. Subsequently, chapter 4 discusses the results from the analysis. After which, chapter 5 discusses and reflects upon the research approach, methodology, and findings. Finally, chapter 6 addresses the research questions, highlights the social and scientific contributions of the study, and offers recommendations for future research.

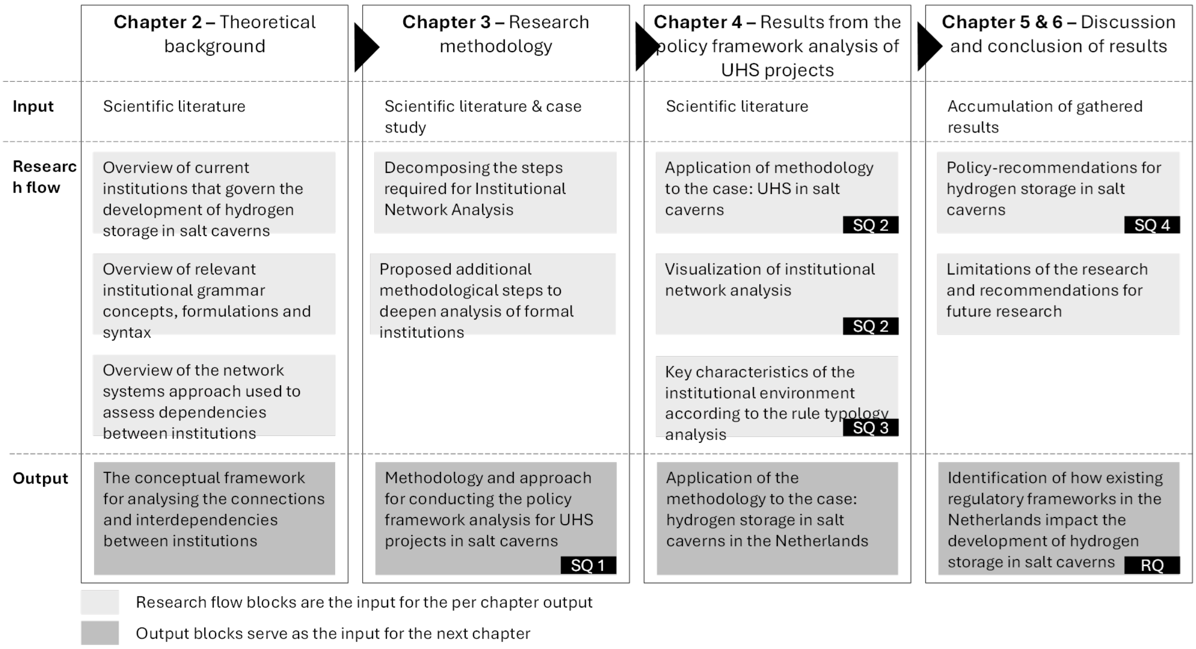

Figure 1.1: Research flow diagram, where SQ refers to sub-question and RQ refers to the research question

2

Research background

The following chapter provides the foundation for this research, necessary for establishing the conceptual framework that serves as a basis for the analysis. The study begins with an exploration of the Dutch regulatory framework for underground hydrogen storage in salt caverns in section 2.1. section 2.2 outlines the institutional analysis, focussing on the key concepts and the IAD framework. Next, section 2.3 discusses institutional statements and the IG 2.0 syntax. Lastly, the conceptual framework is presented in section 2.4.

2.1. Current regulatory framework

Successful realization of large-scale salt cavern storage projects requires the integration of legal and societal elements from the start. New storage initiatives must be backed by clear laws, policies, permitting procedures and contracts to ensure robust support (Groenenberg et al., 2020).

The following section offers background information on the existing regulatory framework for underground hydrogen storage in salt caverns in the Netherlands. It is divided into two parts: the first part covers regulations related to the deep subsurface, while the second part addresses regulations concerning the shallow subsurface and surface.

2.1.1. Deep subsurface

The first component of the regulatory storage framework in the Netherlands relates to the deep subsurface. The deep subsurface is defined as activities that take place 100 meters and deeper(“Mijnbouwwet”, 2024). UHS in salt caverns is located at around 1,200 metres underground, thus the deep subsurface rules and regulations apply (HyStock, 2024). The first step in acquiring the right to explore the deep subsurface area is applying for a licence. Obtaining a licence is obligatory and regulated by the Mining Act. Licences have an ordering function and guarantee a unique right to explore or produce mineral resources, or to store substances in a defined area (den Dulk, 2018; Winters et al., 2020).

The second stage involves obtaining approval for operational plans. According to the Mining Act, various operational plans must be approved within a single licensing area. The first is the production plan, which outlines the development processes and their subsurface consequences, such as subsidence and induced seismic activity. This plan may require updates and modifications during the production phase. Next, the storage plan details how storage will be conducted and the associated possible subsurface impacts. The measuring plan specifies how subsidence, seismic activities, and cavern dimensions will be monitored. Finally, the closing plan outlines the procedures for abandoning the salt cavern (Remmelts & Cino, 2019; Winters et al., 2020).

The Ministry of Economic Affairs and Climate has a decisive role in the duration and quality of both the licensing procedure and the approval of operational plans, and is therefore classified as the competent authority for the Mining Act (“Mijnbouwwet”, 2024). In addition to this, provinces, municipalities and waterboards have the right to advise on the content of the operational plans, thereby adding or changing specific requirements for certain locations within their jurisdiction (Remmelts & Cino, 2019).

2.1.2. Shallow subsurface

The second component of the regulatory framework relates to shallow subsurface, activities less than 100 meters deep, and surface activities. Salt caverns are connected to the surface through pipeline installations, and the salt cavern has a central installation on the surface that regulates the pressure, production, and injection of hydrogen in the caverns (HyStock, 2024). These activities are regulated by the shallow subsurface and surface legislations, which are stated in the Environment and Planning Act. The Environment and Planning Act is the formal institution that brings together rules on spatial planning, housing, infrastructure, nature, and the environment to make environmental legislation more comprehensible. Moreover, the regulatory framework of shallow subsurface and surface activities of underground storage projects is a highly participatory process, involving stakeholders from an early stage, well before the formal decision-making process begins (Winters et al., 2020). The requirements for the stakeholder participation process are outlined in the Environment and Planning Act.

The Act includes two important procedures: the project procedure and the project decision. The procedure requires the competent authority, the Ministry of Economic Affairs and Climate, to be able to justify how the local community has been involved and why a specific procedure has been chosen (“Informatiepunt Leefomgeving”, 2024; Winters et al., 2020). The Act provides several requirements that must be followed for the participatory process, but there is little guidance on how the participation process should be organized. Although the Act does not specify the exact details of the participation process, the competent authority must be able to prove that the interests of all stakeholders are being considered equally at an early stage. In addition to the Ministry of Economic Affairs and Climate, the municipality has a right to advise or give expression of no objection (“Informatiepunt Leefomgeving”, 2024; Remmelts & Cino, 2019).

2.2. Institutional Analysis

This research study uses institutional analysis as a method to understand the relations between institutions, and how these influence the development of UHS in salt caverns. An institutional analysis is used to identify which institutions, activities, and outcomes impact the behaviour and decision-making processes of actors (Ostrom, 2011). It provides a tool for understanding the root of a problem, the nature of individuals and the institutional environment (Ostrom, 2011). As previously discussed in section 1.3, the technical aspect of UHS in salt caverns has been extensively researched, the institutional analysis provides a valid method for studying the relations between institutions and how they influence the development of UHS in salt caverns in the Netherlands.

The approach to the institutional analysis of the case is based on the typology of the Institutional Analysis and Development (IAD) framework as developed by Kiser and Ostrom. E. (1982). The framework emphasizes the action situations that influence the outcomes. This research aims to study the relations and institutions within the institutional environment, the key challenge includes understanding the complex institutional framework, identifying the conflicts and weaknesses and developing appropriate policies to transform it (Lai & Zhao, 2023).

The first part of this section discusses the key concepts related to the institutional analysis. Subsequently, the main institutional framework, IAD, is discussed, including the functions of institutions and the hierarchy in law.

2.2.1. Institutional concepts

Institutions provide mechanisms for resolving conflicts by shaping strategies and opportunities for stakeholder cooperation (Lai & Zhao, 2023). In other words, institutions are defined as the explicit tacit strategies, norms, or rules that indicate to actors what they can, must or must not do in certain situations or within a specific context (Frantz & Siddiki, 2021). These mechanisms oversee infrastructure development, information exchange and decision-making processes. Consequently, a comprehensive understanding of these rules and their diverse functions is imperative for informing better policy decisions (Frantz & Siddiki, 2021).

Formal and informal institutions

To more effectively define institutions identified in the policy documents, a distinction is made between formal and informal institutions. The importance lies in the relative frequency of each Institutional Grammar categorization (as explained in section 2.3), and the understanding such categorization provides into the content of the policy documents (Siddiki et al., 2010)

Although both types of institutions follow similar organizational principles—rules, norms, and strategies that define what is permitted, required, or forbidden—the key differences lie in their structure: (i) formal institutions are documented in writing, whereas informal institutions may not be; and (ii) informal institutions are often more closely related to actual outcomes and behaviours (Siddiki et al., 2010). For example, in the context of UHS in salt caverns, formal institutions would include regulations about environmental permits or safety standards that must be met before a storage facility can operate. These are clear, documented requirements that actors must follow to avoid legal consequences. In contrast, informal rules might include industry norms about how hydrogen operators interact with local communities, or unwritten expectations among companies about sharing best practices for safety, even though such actions are not legally mandated.

Informal institutions are also described as the rules-in-use and relate to social habits that are agreed upon by a collective, often, but not necessarily, verbally (Ostrom, 2005). Whereas formal institutions are called rules-in-form, affecting behaviour through monitoring and enforcements mechanisms (Ostrom, 2005).

Institutional environment and relations

The institutional environment and institutional relations are relevant concepts that are often used within the institutional analysis method. Here, the institutional environment consists of both informal and formal institutions, which influence the individual or organization embedded in the environment (Ostrom, 2005).

In relation to this, strong institutions within an institutional environment are characterized by their full integration into societal behaviour, thus achieving high levels of compliance and effectiveness (Markey et al., 2016). In contrast, weak institutions within the institutional environment, are defined as those that lack the capacity to effectively perform their intended functions, which often results in corruption and inconsistent application of the rules and policies (Markey et al., 2016). For instance, if regulations around UHS safety are not consistently enforced, this could lead to technical failures, creating risks for both the environment and stakeholders. In other words, the compliance with formal institutions relates to the 'strength' of an institution (Siddiki et al., 2011).

However, understanding the institutional environment comes with its own challenges. Institutions are often not individualistic, but interact, influence or are interdependent on other institutions (Kiser & Ostrom. E., 1982). This influence between the various institutions is referred to as the relation between institutions. Specifically, these relations are the connections between institutions that impact other institutions, as well as the related outcome. For example, in UHS projects, safety regulations (formal institutions) may be directly influenced by energy policies or environmental laws, creating a complex web of institutional relations. These relations exist between both formal as informal institutions (Kiser & Ostrom. E., 1982). As a result of the relations between the institutions, an institutional network forms.

2.2.2. Institutional Analysis and Development framework

When analysing institutions, the IAD framework, developed by Kiser and Ostrom. E. (1982), is a proven and widely used research method, used to study the impact of various governance systems on the management of common pool resources. This framework helps understand the interactions and relationships among actors from an institutional perspective by defining key structural elements, see Figure 2.1. For example, in the context of UHS development in salt caverns, the IAD framework provides insights into the institutional structures that influence project approval processes, safety regulations, and community engagement in decision-making. This research study does not focus on all aspects of the IAD framework, therefore, only the relevant concepts are discussed.

The *action arena* refers to the social space in which individuals interact, address problems, assert dominance, interact, or engage in conflicts. It consists of two parts: action situations and actors. An *action situation* refers to interactions among actors, who can be either individuals or groups (Ostrom, 1999). In the case of UHS, actors might include regulatory agencies, energy companies, and local communities, who interact to approve licences, manage operational safety, or negotiate environmental concerns. *Actors* are characterized by four variables: (i) the resources they bring to the situation; (ii) how they value different actions; (iii) how they process and use information; and (iv) their methods for choosing actions (Ostrom, 1999).

Three external variables influence the action arena: *physical/material conditions*, *community attributes*, and *rules-in-use*. This study focusses on the rules-in-use, which refer to the specific regulations that govern UHS projects, such as safety standards for hydrogen storage, or emission reduction targets set by governments (Ostrom, 1999).

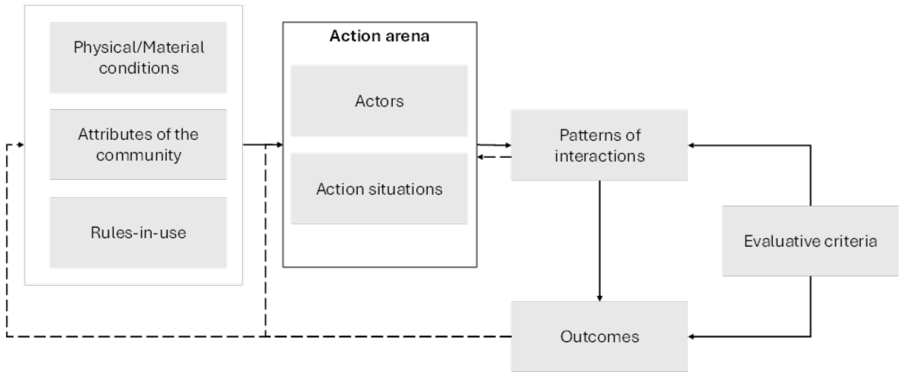

Figure 2.1: Institutional Analysis and Development (IAD) framework. Dashed lines indicate feedback loops, arrows indicate direct causal links (Ostrom, 1999)

The functions of institutions

A key aspect of the IAD framework is identifying the rule configurations of action situations and studying the effects on the structure of situations (Lai & Zhao, 2023; Ostrom, 2011). The framework defines seven rule types that affect the action situations, each of the rules regulates a different institutional aspect. Within the action arena, *positions* categorize actors, and assign them certain responsibilities. Meaning that in a certain community, all *actors* occupy a distinct role and have specific responsibilities. *Actions* in turn refer to the behaviour actors value based on its perceived benefits. Actors, positions, and actions are respectively governed by boundary rules, position rules, and choice rules as can be seen in Figure 2.

Boundary rules determine the conditions under which an actor is able to participate in an action situation, specifying their attributes, resources and the potential consequences of leaving. These rules determine the eligibility for positions that are regulated by *position rules*, which allocate categories of actors to specific roles within the action arena. Lastly, *choice rule*s define the options available to actors with respect to the actions they are able to take (Ostrom, 2011).

When a certain action is taken, the information rules and aggregation rules come into play. *Information rules* regulate the type and flow of information, where *aggregation rules* define joint decision-making by outlining the number of actors needed to make a collective decision. These rules are crucial in action situations where collective action is necessary, such as in regulatory decision-making or public consultation processes for UHS in salt caverns. For instance, decisions on safety regulations might require approval from multiple agencies, each contributing their knowledge and authority to the decision.

Next, the *scope rules* limit the potential outcomes by linking these outcomes to the actions the actors can take. For example, in the context of UHS, scope rules might restrict certain storage methods based on safety guidelines. Finally, *payoff rules* influence incentives by defining the rewards or sanctions associated with particular actions and outcomes (Ostrom, 1999). For instance, actors may be incentivized to follow safety protocols in UHS operations due to legal and financial consequences tied to non-compliance.

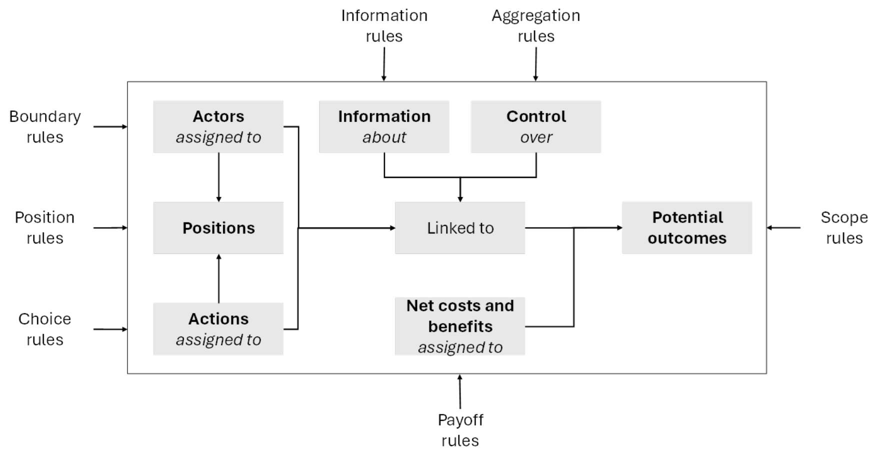

Figure 2.2: The seven types of rules that affect the elements of the action situation of the IAD framework (Ostrom, 1999)

Hierarchy and level of institutions

When studying the various institutions in the Netherlands, it is important to keep in mind that there is a hierarchy of institutions. The hierarchy of law is important, as there are possibly several public authorities that enact within their own power laws, which might be contradictory. In order to avoid these situations, there is a hierarchy (Dutch Civil Law, 2024). Within the hierarchy of these rules of law, international treaties form the highest ranked regulation, it has priority even over the Dutch Constitution as can be seen in Figure 2.3. The importance of keeping in mind this hierarchy relates to the interdependencies and relations between institutions. For instance, often institutions interact and overlap in such a way that higher-level rules might constrain or enable lower-level rules. Moreover, the higher one moves up the hierarchical ladder, the more complex and time-consuming it becomes to amend an institution. From an actor perspective, this hierarchy influences the boundaries within which the possible actions are defined and thus the outcomes to be obtained (Clegg et al., 2016).

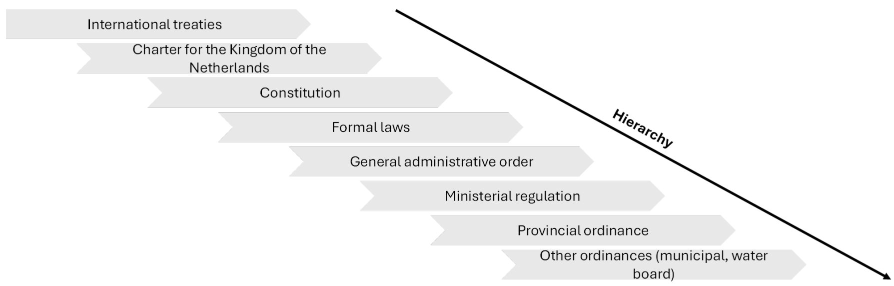

Figure 2.3: Overview of hierarchy of formal institutions in the Netherlands

2.3. Institutional statements and grammar

2.3.1. Institutional statements

The IAD framework emphasizes the patterns of interactions and outcomes that emerge within an action arena, where both decision-making and the evaluation of the outcomes occur. Within the action arena, the three types of institutional statements that might occur are either rules, norms, or strategies (Crawford & Ostrom, 1995). IG is a theoretically grounded analytical approach for analysing and decomposing the syntactic structure and meaning of directives within institutions and their resulting behavioural outcomes (Crawford & Ostrom, 1995; Watkins & Westphal, 2015).

Policy directives are also known as institutional statements in the IG syntax. Crawford and Ostrom (1995) have defined an institutional statement as rules that regulate the actions of actors, by either specifying the absence or presence of certain constraints, or by defining the boundaries of the system in which actors interact (Crawford & Ostrom, 1995; Frantz & Siddiki, 2021). Institutional statements include amongst others public policies, social norms, legislation and administrative regulations.

2.3.2. Institutional Grammar 2.0

The second important aspect of the IG syntax relates to the identification of generalizable components of institutional statements. This practice involves recognizing elements that are common to statements and observed across various institutional domains and types (Frantz & Siddiki, 2021). To do so, the ADICO syntax was developed. This grammar offers a semiformal description of institutional rules, making them accessible for both structured policy coding as well as economic analysis (Frantz et al., 2013).

Important challenges highlighted by Basurto et al. (2010) in understanding and applying the ADICO syntax are: (i) the complexity of identifying the Attribute; (ii) uncertainty regarding how to code explicit Deontic statements; and lastly, (iii) difficulties in distinguishing between the Aim and the Conditions. As a result, Basurto et al. (2010) proposed an extension of the ADICO syntax: the Object. The Object reflects either the animate or inanimate part of a statement, which receives the action or the outcome of the action. The action is described in the Aim, which is in turn executed by the Attribute of the statement (Basurto et al., 2010). A description of each of the ABDICO components is given in Table 2.1. Adding the Object to the ADICO syntax facilitates the interpretation of the institutional statement, as it helps to distinguish between the actor, or the Attribute, from what the actor is acting upon, or, the Object. In conclusion, by minimizing the uncertainty related to coding, adding the Object increases the reliability of the coding syntax (Basurto et al., 2010). It allows for the clear differentiation of statement components, which leads to better and more reliable analysis.

Table 2.1: Overview of ABDICO syntax from Institutional Grammar (Crawford & Ostrom, 1995; Siddiki et al., 2011)

Component of Institutional Grammar syntax	
Component	**Description**
[A] **A**ttribute	Captures the *actor responsible* for a given institutional statement, either explicit or implicit
[B] O**b**ject	The receiver of an action and performed by the actor, either animate or inanimate entities
[D] **D**eontic	The prescriptive operator which specifies whether an Attribute is *required*, *allowed*, or *forbidden* to perform the Aim under the given conditions
[I] A**i**m	The activity in an institutional statement associated with the Attribute, which can be either co-occurring (and), inclusive disjunctive (or), or exclusive disjunctive (xor)
[C] **C**onditions	The *temporal, spatial or procedural* parameter that describes *when, where and how* the statement applies
[O] **O**r else	The payoff (sanction) associated with the fulfilment of the institutional statement

2.4. Conceptual framework for analysis

In Figure 2.4, the conceptual overview of the research outline is presented, illustrating the cascading sequence of steps in the analysis framework. The process begins with gaining a thorough understanding of the research context, where the need for UHS projects and the associated challenges are examined. Following this, the research background is used to establish key concepts necessary for the analysis. The next step involves collecting data by investigating the institutional environment, which comprises various policy documents. Once the institutional environment and relationships are mapped, these diagrams are analyzed in detail. Finally, a more in-depth examination of the formal institutions is conducted to provide deeper insights.

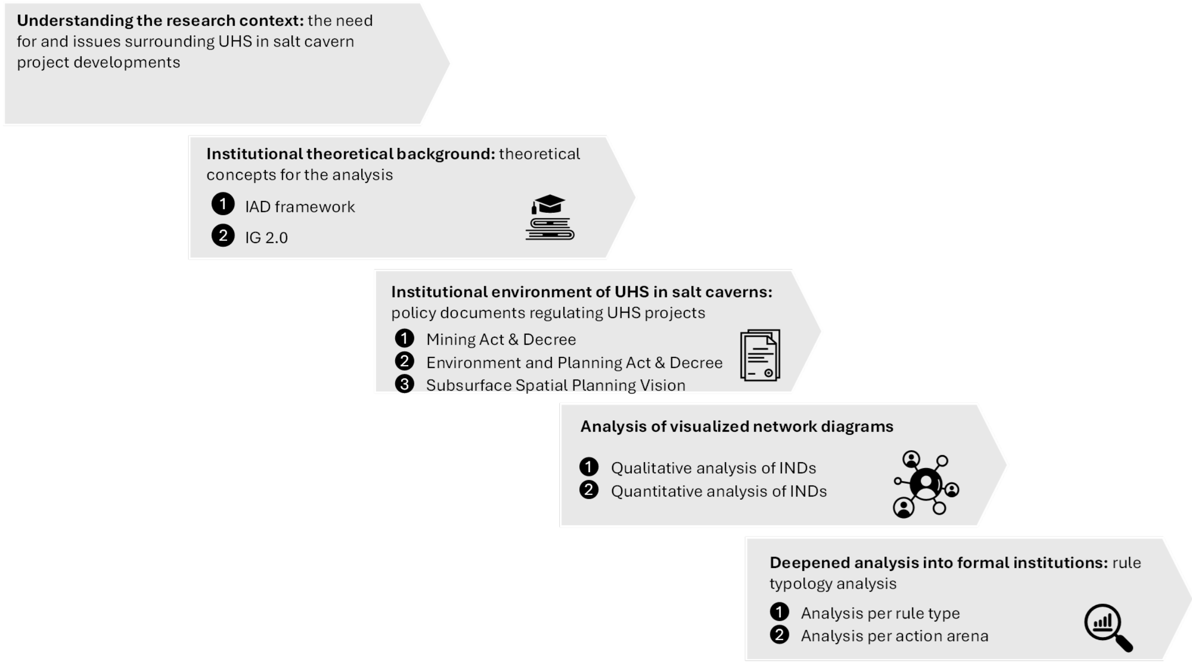

Figure 2.4: Conceptual framework for the thesis research

3

Research methodology

In the current academic literature, various approaches exist for analysing institutional networks.

Firstly, Lubell (2013) present an updated concept of the Ecology of Games (EG) framework, originally developed by Long (1958). The EG framework addresses institutional complexity by adopting a complex adaptive system perspective. This perspective facilitates an analysis over time, where policy outputs and outcomes result from decisions made at different stages (Lubell, 2013). EG extends the IAD framework and aims to generate hypotheses about factors influencing institutional change and behaviour (Cornwell et al., 2003; Lubell, 2013).

Secondly, the Network of Adjacent Action Situations (NAS) approach, developed by McGinnis (2011), is based on the IAD framework and rule typology. This method analyses interactions within a biophysical and socio-economic context across multiple levels—operational, collective choice, and constitutional (Kimmich et al., 2023; Ostrom, 2011). The NAS method examines how outcomes in one action situation might influence actions in adjacent situations (Kimmich et al., 2023), thus improving the understanding of interactions between various action situations.

Thirdly, Olivier (2019) propose the Networks of Prescribed Interactions (NPI) method. This method focuses on understanding interactions between actors as guided by institutional directives, analysing the parameters that constrain and guide these interactions. The NPI method combines Social Network Analysis (SNA) with the IG syntax to capture patterns of interactions mandated by formal rules (Bodin, 2017; Olivier, 2019).

Although these frameworks have been extensively researched and applied, they do not fully align with the needs of this research. The EG framework focuses on community-ecological aspects, which are not considered here. Both the NAS and EG frameworks do not address the relations between formal institutions directly. Additionally, while the NPI method examines relations involving animate objects (actors), it does not sufficiently address how inanimate objects (e.g., contracts) and the context of policy directives influence the institutional environment.

To address these gaps, this research employs the Institutional Network Analysis (INA) method, proposed by Mesdaghi et al. (2022). The INA method is selected for its ability to systematically explore the institutional environment and network, encompassing both actors and inanimate objects. Building on the IAD framework, the INA method offers a structured approach for mapping and visualizing institutional relations, recognizing patterns within the institutional network. By linking institutional statements through inanimate objects such as contracts, the INA method captures the chain of actions performed by individual actors. Mapping the Institutional Network Diagram (IND) provides a clear visual representation of the formal institutions.

This chapter outlines each step of the research methodology as proposed by the INA method. section 3.1 details the data collection process, section 3.2 explains the clustering and coding of the collected data, and section 3.3 discusses the formalization of institutional statements using the ABDICO syntax. section 3.4 presents a methodological enhancement to the INA method, and section 3.5 describes the process of mapping and analysing INDs. Finally, section 3.6 covers the validation and verification of the INA method and its results.

Figure 3.1: Overview of the steps of the Institutional Network Analysis as proposed by Mesdaghi et al. (2022), including the proposed methodological additions

3.1. Data collection: policy documents

The first step of the INA method involves comprehensive data collection. Where the INA method utilizes two approaches for data collection, both desk research and interviews, this study primarily employs desk research to dissect policy documents relevant to UHS in salt caverns, focussing on formal institutions. Key documents include policy directives, legislative texts and strategic documents.

A comprehensive desk research is conducted to compile a list of relevant institutional data, including both policy directives, legislative texts and strategic plans. The documents were selected based on relevance for the context of UHS in salt caverns. To ensure a thorough and exhaustive search, a detailed search string was developed (see Table 3.1) and translated into Dutch, incorporating a range of synonyms and related terms. The approach allowed for the inclusion of various terminologies used in different legal, policy, and academic sources, ensuring that no relevant documents were overlooked.

The selection criteria focused on the documents that directly address underground hydrogen storage or touch on broader regulatory, environmental, and safety concerns that could impact the development of such projects. This included not only established national policy documents, but also national strategic visions, as these documents often provide insight into long-term goals and priorities that influence regulatory frameworks.

The search yielded a variety of documents as outlined in Table 3.2. Each document was carefully reviewed for its applicability to UHS in salt caverns. This rigorous process ensured that the most relevant and up-to-date institutional data were included, providing a solid foundation for understanding the regulatory environment in which UHS project developers must operate.

Table 3.1: Search string used to identify relevant policy documents and directives

Context	Keywords
Storage Salt cavern Underground Subsurface Surface	Hydrogen Gas Gaseous substances Natural gas Minerals Storage of substances

Table 3.2: Overview of policy documents selected for the research context

Level	Policy document
Dutch national level	Mijnbouwwet (Mining Act) Mijnbouwbesluit Omgevingswet (Environment and Planning Act) Structuurvisie Ondergrond

In addition to the policy documents stated in Table 3.2, the search led to the identification of additional legislation, including the Energy Act, Seveso Directive, and Decree on Activities in the Living Environment (Besluit Activiteiten Leefomgeving, or BAL). However, specific reasons lead to the exclusion of these legislations from this analysis. First of all, the new Energy Act, passed by the House of Representatives on June 4 2024, aims to replace the Electricity Act (1998) and the Gas Act, while also integrating European regulations. Yet, this Act must still pass through the Senate and is not yet officially in use (Jetten, 2024). Consequently, it is not included in the current scope of this research.

Furthermore, the Seveso Directive, which established safety and environmental standards for the storage of hazardous substances, including hydrogen, has been incorporated into the Environment and Planning Act as of January 1 ("Omgevingswet: Seveso-inrichting", 2024). This incorporation renders a separate analysis of the Seveso Directive redundant. Similarly, the BAL, which outlines rules and regulations for activities that may affect the living environment, has also been integrated into the Environment and Planning Act ("Inhoud Besluit Activiteiten Leefomgeving", 2024). This integration makes the individual analysis of the BAL unnecessary as well. By excluding these documents, the research can maintain a focused and relevant analysis of existing and applicable policy documents.

3.2. Data coding & clustering: defining the action arenas

The second step of the INA method is coding and clustering informal data retrieved in the data collection step. As this research does not focus on the informal institutions retrieved from (expert) interviews, this research deviates from the approach described by Mesdaghi et al. (2022) as the coding and clustering step is limited. Therefore, the following section is limited to the identification of the action arenas.

An action arena is defined as a circumstance of resource governance, where actors are presented with a set of rules and potential outcomes, that jointly produce outcomes (Lai & Zhao, 2023). The selection of the arenas is based on the initial analysis of the institutional environment in the research background, and the author's understanding of the institutions related to UHS in salt caverns thus far. The action arenas used in this research are the following: (i) project initiation; (ii) community and stakeholder engagement; (iii) closure, safety, and subsidence control. These three action arenas were selected as they correspond to the logical phases within large-scale project development, namely: initiation, planning, execution, monitoring and controlling, and closure (Laporte & Chevalier, 2015). The next chapter will elaborate further on the choice for each action arena (see chapter 4).

3.3. Formalizing institutions

After defining the action arenas, the research continues to formalize the institutions. This step aims to identify the institutional statements found in the policy documents. To this end, the Institutional Grammar 2.0 syntax is applied. In order to successfully apply the ABDICO syntax to the policy documents, this research utilizes the steps established by Basurto et al. (2010). The approach deviates slightly from the method proposed by Basurto et al. (2010) by extending the steps with best-practice experiences, and eliminating the step which codes all institutional statements as either rules, norms, or strategies as this research solely focusses on the distinction between formal and informal institutional statements.

In Figure 3.2 the steps for analysis are presented. First the documents are carefully read, highlighting relevant articles. After which, the relevant articles are documented and logged with their appropriate document type and article number. Next, each of the rules is assigned to one of the action arenas. Consequently, the institutional statements are coded according to the ABDICO syntax, using the standardized template as described below and in Table 3.3. Lastly, each statement is assigned to one of the rule typologies, see Table 3.4.

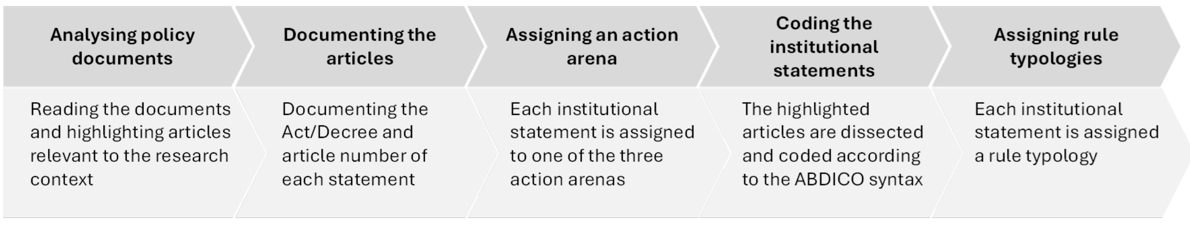

Figure 3.2: Flow chart indicating the process for formalizing the institutions

This research employs a standardized template for formalizing institutions, as illustrated in Table 3.3. The template offers specific options for several formalizing steps to ensure consistency. For instance, [D] Deontic element is restricted to "may", "must", or "must not" and the type of [B] Object is designated as either inanimate or animate. Moreover, each statement automatically receives an ID number, which enables a simplified process for referring to another statement in the [O] Or else column, where the number ID can be entered, and the program automatically links the statements. These coding elements are selected to standardize the process and streamline the resulting INDs.

Table 3.3: Template for coding the institutional statements

Statement type	Attribute	Deontic	Aim	Direct object	Type of direct object	Indirect object	Type of indirect object	Activation condition	Execution constraint	Or else
Formal Informal	-	May Must Must not	-	-	Inanimate Animate	-	Inanimate Animate	-	If…	-

In addition to the standardized template, this study incorporates four additional columns. The columns are indicated in Table 3.4, where the rows indicate the options to chose from. The inclusion of the document type and article number enhances transparency, ensuring that the institutional statement scan be easily traced back to their sources. Furthermore, each institutional statement is categorized into one of three action arenas, facilitating the construction of the INDs for each arena. Lastly, this study integrates a rule typology analysis. Each institutional statement is assigned to one of the rule typologies to deepen the analysis within the framework, subsection 3.4.1 will further specify the method for this analysis.

Table 3.4: Added columns to the standard template

Document type	Article	Action arena	Rule typology
Mining Act Mining Decree Environment and Planning Act Environment and Planning Decree	#	1. Initiation phase 2. Community and stakeholder engagement 3. Closure, safety, and subsidence control	Position rules Boundary rules Choice rules Aggregation rules Information rules Scope rules Payoff rules

One of the main challenges in formalizing institutional frameworks is ensuring a comprehensive and thorough search and analysis of the selected policy documents. For instance, the Environment and Planning Act comprises approximately 350 articles, many of which are not relevant to the specific context of this research study. To address this challenge, policy documents are reviewed multiple times with intervals of several days between readings to minimize the risk of overlooking any articles. Furthermore, targeted analyses by researchers specializing in specific sections of the policy documents are utilized. For example, a study by Winters et al. (2020) provides an in-depth examination of the legal requirements related to UHS in the Environment and Planning Act.

3.4. Methodological additions to INA

The following section discusses the steps added to the INA analysis. First, in subsection 3.4.1 the rule typology analysis is explained, which includes the proposed steps for analysis. Second, in subsection 3.4.2 the method for a component level analysis of the IND is presented.

Expanding the INA method by addressing the rule typology analysis provides a deeper and more comprehensive understanding of the formal rules governing UHS in salt caverns. The rule typology analysis reveals the dominance and composition of rules within the institutional framework. This enhanced analysis facilitates a more nuanced exploration of institutional diversity and characteristics, which enables a more informed policymaking process (Lai & Zhao, 2023). Moreover, the component-level analysis is utilized to systematically analyse the links between institutional statement. This analysis provides insights into the bottlenecks that hamper the implementation of formal institutions by visualizing what the motivation is behind the link (Ghorbani et al., 2024).

3.4.1. Rule typology analysis

Formal rules play a central role in the development of UHS facilities by shaping the institutional environment and informing policymaking decisions (Lai & Zhao, 2023). This research analysis the structure and functions of these rules, using the IAD framework's rule typologies, to manage institutional complexity and gain insights into institutional arrangements (Lien et al., 2018). By examining the number and composition of the seven generic rule types, the study reveals dominant rule categories, and explores institutional diversity and characteristics (Lai & Zhao, 2023).

Incorporating rule typology analysis into the INA method provides a deeper understanding of the formal institutions governing UHS in salt caverns. The value of the analysis lies in the ability to identify and quantify the types of rules that impact the UHS projects significantly, by emphasizing the rules that control actors' actions and the availability of information (Lai & Zhao, 2023). Moreover, the analysis highlights regulatory gaps or areas for policy improvement, supporting the comparative assessment of institutional diversity across action arenas.

Previous studies often focus on analysing [I] Aims as indicators of rule types (Lien et al., 2018). However, recent methods include [A] Attributes, which shed light on actor roles (Siddiki et al., 2022). This research follows the approach by Lai and Zhao (2023), offering a more systematic review of rule typologies within the institutional network.

This method aligns with INA, using IG 2.0 to break down policy documents and analyse them with IAD's rule typologies. It combines quantitative analysis — assessing the number and composition of rules across action arenas — with qualitative analysis to evaluate their functions in the action arenas (Lai & Zhao, 2023). Building on this framework, additional steps to the INA methodology are proposed below.

1. Identify [I] Aims for each rule in the IND — refer to Table 3.5 for an overview of possible aims corresponding to the rule types.
2. Classify all [I] Aims by rule type — assign each aim to one of the seven rule types based on the IAD typology.
3. Analyse rules within each action arena — examine the composition of rules and categorize the types within each action arena.
4. Visualize the rule typologies — create graphs to illustrate the distribution and composition of rule types across the action arenas.

Table 3.5: Overview of the rule typology and types of Aims the rules may have

IAD rule typology	Type of [I] Aims the rule may have
Position rules	Establish, consist, be
Boundary rules	Appoint, cease, hold, nominate
Choice rules	Coordinate, authorize, review, use, receive, store, approve, determine, decide, agree
Aggregation rules	By vote, by mutual agreement, consult, obtain, undertake, jointly, with
Information rules	Give, submit, send, disclose, publish, notify, specify, include, indicate
Scope rules	Alter, cause, exceed, increase, consider, take into account, comply with, in accordance with
Payoff rules	Pay, contribute, meet, receive, charge, recover

Classifying institutional statement can be challenging when they might fit into more than one rule typology. The final classification often depends on the objective decision made by the researcher. To address this classification challenge and ensure consistency in the results across the three action arenas, two precautions are taken. First, when a decision is made between two rule typologies, the choice is highlighted and logged. This practice ensures that when a similar decision arises in another action arena, the same classification is consistently applied. Second, when uncertainty persist regarding which rule typology to select, a thorough analysis of the complete ABDICO syntax is conducted, focusing on the [D] Deontic and [B] Object elements. This detailed examination can provide additional insights into the appropriate rule typology for a statement.

By implementing these precautions, the research aims to maintain consistency and rigour in the classification process, ultimately contributing to a more accurate and reliable analysis of the institutional environment governing UHS projects.

3.4.2. Drivers behind connections

The INA method represents network diagrams where institutional statements are dissected to represent the nodes in the network. Consequently, there are connections between the institutional statements, which together form an institutional network. This visual representation then reflects a component-level diagram in which the syntactic components are the distinctive nodes, and where the remaining components are used as the links between the nodes (Ghorbani et al., 2024). Visualizing the institutional statements using a component-level approach, which focusses on the reasoning behind a specific connection, enables a robust understanding of the situations in which actors initiate an action and how those actions are qualified. The method is proposed by Ghorbani et al. (2024) and provides an extension of the INA method, an overview is given in Appendix B.

The diagram enables three ways in which institutional statements can be connected to form an institutional network diagram: actor-driven, outcome-driven and sanction-driven connections. Institutional statements initiate with an activation [C] Condition to provide a better visualization of how context provides the condition for carrying out actions as conveyed in institutional statements.

1. *Actor-driven connection* — denotes the link between a direct or indirect animate [B] object of a statement and the [A] Attribute of another statement. Mapping the actor-driven connection is only possible when the [A] Attribute or [I] Aim or the [B] Object and the [I] Aim of the first statement appear in the activation condition of the second statement.
2. *Outcome-driven connection* — appears when the inanimate direct [B] Object of a statement or its execution constraint is connected to the activation [C] Condition of another statement if that [B] Object and the [I] Aim, or the execution constraint and the [I] Aim appear in the condition of the second statement. The connection visualizes how one statement can instantiate a discrete context which activates a second statement.
3. *Sanction-driven connection* — when visualizing nested statements, the sanction of a statement is a statement in itself. This structure is captured by connecting the [I] Aim of a statement to the activation condition of another statement if the opposite of that [I] Aim is present in the second statement.

3.5. Analysing the institutional framework for UHS in salt caverns

3.5.1. Drawing the institutional network diagrams

For each of the identified action arenas, a separate IND will be made. The IND is based on the subset of the total institutional statements per action arena, identified through the analysis of the selected policy documents. An advantage of using the institutional statements as the basis for the IND, is that it enables a comprehensive overview of information, in which both the actors within the network are identified and the relations between the institutions.

The step-by-step overview of the procedure for constructing the IND draws upon the research by Mesdaghi et al. (2022). Each phase of the process is aligned with the IAD framework and IG 2.0 syntax and the visual representation of the component or actions, the precise steps are presented in Appendix B. While the approach largely adheres to the steps outlined by Mesdaghi et al. (2022), it diverges in that it omits the process of colour coding strategies, rules, and norms. Given that this study is confined to the analysis of formal policy documents, this step is excluded from the methodology. In addition to this, the steps for the connections between institutional statements, as outlined in subsection 3.4.2, are added to the methodology.

3.5.2. Analysing the institutional network diagrams

When using the INA method to map the institutional environment and construct an IND, there are various ways to analyse the IND, which will be employed in this research study. The analysis of the network diagrams is based on a qualitative and quantitative assessment, where the former discusses what can be seen from the visualized networks, and the latter uses various numerical methods to provide insights that cannot be directly seen from the visualization. Lastly, a high-over assessment of the network arenas assesses how the arenas might be connected to each other.

Qualitative assessment

Institutional voids refer to the absence or inefficiency of the institutions within the institutional environment and are defined as institutions failing to support functioning markets (Dieleman et al., 2022). Especially emerging markets, such as UHS in salt caverns, are characterized by institutional voids as traditional market mechanisms and regulatory frameworks are often still underdeveloped (Khanna & Palepu, 2010). Analysing the institutional statements, their rule typology and the institutional hierarchy can reveal any institutional voids in the institutional environment.

As described in section 2.2 of the research background, relations between institutions exist within the institutional environment. As a result of these relations, institutional conflicts may arise. Existing research often defines institutional conflicts as inter-organizational conflicts (Pache & Santos, 2017) or conflicts between international governments (Gehring & Oberthur, 2009). However, within this research context, institutional conflicts refers to when the outcome of institutions differs from what was predicted or meant beforehand. This can happen in two ways. First, an institutional conflict can arise when various institutions are in contrast, and aim to influence actor behaviour towards different outcomes. Second, a conflict can arise when the outcome of a formal institution derived from a policy document is in contrast with a policy goal as described in a non-legally binding policy document, such as the Dutch government's national vision.

Lastly, the analysis extends to the institutional levels within an action arena. As outlined in section 2.2, the hierarchy of institutions within this research is categorized into three groups: Acts, Decrees, and non-legally binding documents. The interplay between these levels can be examined to understand how higher-level regulations, such as Acts, influence, and shape the enforcement of lower-level decrees. The analysis provides insights into how institutional authority is distributed and how compliance is ensured, revealing potential areas of conflicts or voids.

Quantitative assessment

Network Analysis is an academic discipline that utilizes networks and graph theory to investigate structures (Wang et al., 2018). Network metrics addresses the structure and pattern of relations. The approach describes how the structures of these relations influence behaviour, and identifies both the cause and effects of such structures (Wang et al., 2018). According to Easley and Kleinberg (2010), a network is defined as a set of nodes (institutional statements) and links (relations), where the emerging structure contributes to explaining the relations between the institutions. Within the network, the focus then transfers from individual institutions and their properties, to the relations between the institutions. The relations between institutions aggregate into ties, and patterns of links reveal networks (Haythornthwaite & St, 1996).

Three metrics used to analyse network diagrams are: centrality, embeddedness and the density. Each of the metrics provides valuable additional information on the dynamics and dependencies within the institutional network, insights that are not immediately visible from the network diagrams. An overview of the metrics and their descriptions is given in Appendix C.

The centrality metric measures the 'importance' of an actor in the network, where importance is measured based on the number of links an actor has to others and relates to the influence an actor has in the network (Easley & Kleinberg, 2010). An actor with a high degree of centrality therefore has an important role in the network. This research focusses on structural embeddedness, which specifically refers to factual characteristics that relations and actor's networks may have (Daub, 2009). A high degree of embeddedness implies there are many institutions dependent on each other for their execution. Lastly, the density quantifies the reliance of institutions on other institutions for their execution. A high density indicates that many institutions in a network diagram depend on the execution of other institutions for their own implementation (Mesdaghi et al., 2022). An overview of these network metrics is provided in Appendix C.

Connecting action arenas

Since the underground hydrogen storage in salt caverns relates to all phases described in the action arenas – deep subsurface, shallow subsurface, and surface – relations exists between the INDs. In light of this, the INDs can be linked to one another, such that the connections between these INDS can be studied as well.

3.6. Research verification and validation

Both verification and validation are important steps in the research process. Verification addresses the accuracy, consistency, and completeness of the research. Verification will be conducted through two primary approaches. Firstly, the results are presented and discussed with both Dr. Amineh Ghorbani and Ir. Renske van 't Veer, both of whom are experts in the INA approach. Secondly, an integral component of the verification involves the application of a large language model (LLM) developed by Kaninik Baradi, a fellow CoSEM master student. This model is utilized to analyse and decompose the institutional statements in the selected policy documents. The findings are then cross-verified with those from the author's own analysis to ensure comprehensive coverage of the institutional statements. The results of the validation sessions will be discussed in chapter 6.

Subsequently, validation of the research results serves to ascertain the scientific and societal relevance, to confirm the theoretical foundations, and identify any discrepancies or oversights. Typically, validation involves rigorous testing of the research outcomes through expert interviews, involving relevant academics and stakeholders in the UHS context. However, due to the limited time and scope of this research thesis study, conducting a thorough validation is not included. The absence of a full validation underscores the need for future research to thoroughly test the findings of this thesis.

4

Results from the policy framework analysis for UHS in salt caverns

This study focuses on the analysis of three specific action arenas: (i) project initiation; (ii) community and stakeholder engagement; and (iii) closure, safety, and subsidence control. As previously mentioned in section 3.2, these steps align with the phases of large-scale energy projects: initiation, planning, execution, monitoring and controlling, and closure (Laporte & Chevalier, 2015).

The relevancy of the first action arena lies in the fact that obtaining permits is a foundational step in any subsurface project. Without approval from the competent authority, no project can commence. The action arena details the procedural requirements needed to ensure regulatory compliance, which lays the groundwork for the project legitimacy. The second action arena relates to the social acceptance of local communities and stakeholders, which is critical for successful implementation of large-scale energy projects (Enserink et al., 2022). The action arena visualizes the rules related to the participatory approach as mandated by the Environment and Planning Act. Lastly, the third action arena relates to the critical importance of ensuring safety and environmental projection in subsurface storage operations, as outlined in the Mining Act. The inclusion of this action arena underscores the commitment to operational safety and long-term environmental protection.

- *Project initiation* — initial phase of developing UHS projects in salt caverns focuses on securing the necessary permits and licenses. These include permits for exploration, extraction, storage, and environmental compliance. All permits are evaluated and issued by the competent authority, the Minister of Economic Affairs and Climate. Concurrently, the project must submit various plans for assessment by the Minister, covering production, storage, measurement, and closure strategies.
- *Community and stakeholder engagement* — This second action arena emphasizes involving local communities and stakeholders impacted by UHS projects. Key stakeholders include provinces, municipalities, water boards, and local communities. Various local authorities have advisory rights regarding the assessment or content of permits and plans. Additionally, comprehensive procedures for engaging local communities are required. This involves disseminating information and knowledge extensively and empowering communities to propose alternative solutions to the issues at hand.
- *Closure, safety, and subsidence control* — The final action arena pertains to the management of the facility, specifically the operation and maintenance of salt caverns used for hydrogen injection and withdrawal. The Mining Act mandates continuous monitoring of potential ground movements associated with these activities. Additionally, a Seismic Risk Analysis (SRA) must be conducted to explicitly identify safety risks. This analysis is rigorously reviewed by the State Supervision of Mines (Staatstoezicht op de Mijnen or SodM) to ensure compliance with safety regulations and to mitigate risks associated with seismic activities.

The following chapter presents the results of the policy framework analysis for UHS in salt caverns. It begins by discussing the assumptions underlying the research (section 4.1), followed by a review of the selected policy documents used in the analysis (section 4.2). Next, the chapter examines the network diagrams, starting with a qualitative analysis (section 4.3) and proceeding to a quantitative analysis (section 4.4). It then explores the connections between action arenas (section 4.5) before concluding with a discussion of the results from the rule typology analysis (section 4.6).

4.1. Research assumptions

Several assumptions are integral to the effective construction of the institutional network diagrams. These assumptions deviate from the original Institutional Grammar 2.0, IAD framework and INA methodology. The primary assumption concerns rule typology. According to Crawford and Ostrom (1995), rules are characterized by formal sanctions – or the [O] Or else component – without which a rule is merely a norm. However, the formal institutional statements analysed in this study are extracted from various policy documents, and are thus interpreted as formal rules with obligatory responsibilities for the actors involved. Consequently, categorizing these statements as norms would be inappropriate, given the obligation to adhere.

A second important assumption concerns the generalization of institutional statements associated with individual members of a project consortium to a single entity labelled 'Project developer'. This approach implies that despite the involvement of multiple companies responsible for various development phases, they are collectively referred to under this unified term. Such a generalization may result in the loss of specific details pertaining to individual companies. Nonetheless, this simplification is essential for maintaining a comprehensive IND overview, which facilitates a more effective analysis of the institutional environment.

4.2. Selected policy documents for analysis

4.2.1. Mining Act & Decree

The Mining Act, effective from May 2024, regulates the use of natural resources in the deep subsurface, including the exploration, extraction, and storage of minerals and geothermal energy. With certain exceptions, this legislation applies exclusively to minerals located at depths greater than 100 meters and to geothermal energy at depths greater than 500 meters. The Act also requires the dissemination of information regarding the use of deep subsurface resources ("Domein Mijnbouwwet in de Basisregistratie Ondergrond", 2022; "Mijnbouwwet", 2024).

When analyzing the institutional environment for UHS in salt caverns, the Mining Act is highly relevant as it establishes the legal requirements and standards necessary for the safe and efficient use of subsurface resources. It ensures that hydrogen storage operations are conducted within established legal boundaries. The Act also outlines the permitting process for subsurface activities, requiring any UHS project to obtain the necessary permits to comply with safety, environmental, and technical standards. Furthermore, the Act mandates detailed reporting on subsurface resource use, ensuring transparency and allowing relevant authorities to monitor and regulate hydrogen storage operations and their impacts ("Mijnbouwwet", 2024; van Binnenlandse Zaken en Koninkrijksrelaties, 2024).

In addition to the Mining Act, the Mining Decree (January 2024) ("Mijnbouw besluit", 2024) complements the Act by providing detailed rules and guidelines necessary for its practical application. While the Mining Act sets out the broad legal framework for mining and subsurface activities, the Mining Decree specifies operational standards and procedures. It details safety standards, environmental protection measures, and permit application procedures, all of which are crucial for the UHS context.

4.2.2. Environment and Planning Act & Decree

The Environment and Planning Act (Omgevingswet), effective from January 2024, regulates the spatial environment where citizens live and work. It consolidates and simplifies regulations related to visible and audible aspects of the external environment. This Act replaces existing laws and regulations concerning spatial planning and environmental issues. It applies to all citizens, organizations, and businesses in the Netherlands, including those involved in UHS projects. Implementation of the Act is managed through the Environmental Desk (Omgevingsloket), a centralized portal that provides location-specific regulatory information, permit requirements, notification obligations, application submissions, municipal consultations, and application tracking ("Informatiepunt Leefomgeving", 2024).

The Act promotes community and stakeholder engagement in planning and projects, thereby enhancing the success of innovative initiatives ("Informatiepunt Leefomgeving", 2024). Additionally, it allows municipalities to adapt rules to local needs, mandates faster decision-making processes, and adopts a comprehensive approach to evaluating environmental factors such as energy, sustainability, and social impact ("Omgevingswet", 2024).

Complementing the Environment and Planning Act, the Environment and Planning Decree (Omgevingsbesluit) from May 2024 provides a detailed overview of the rules and guidelines established by the Act (similar to the Mining Decree). The Decree offers specific regulations and guidelines necessary to achieve the Act's objectives, including procedural steps, standards, and compliance criteria ("Omgevingsbesluit", 2024). This hierarchical structure ensures that while the Act outlines broad requirements for projects like UHS in salt caverns, the Decree specifies the precise operational details. Together, these policy documents create a comprehensive regulatory framework essential for the successful implementation of UHS projects in the Netherlands.

4.2.3. Subsurface Spatial Planning Vision

The deep subsurface appears to offer vast space, with minimal conflicts between various uses so far. However, given long-term goals related to energy and drinking water supply, it is crucial to develop a strategic vision for subsurface utilization to avert potential future conflicts. This vision should not only address the allocation of physical space within the deep subsurface but also consider the above-ground facilities and pipelines required for mining activities, which impact the shallow subsurface and groundwater layers. To address this, the Dutch government has developed the Subsurface Spatial Planning Vision (structuurvisie ondergrond, hereafter: Vision) (*Structuurvisie Ondergrond*, 2018).

The Vision outlines structural policies for activities of national significance, including drinking water provision and mining activities such as natural gas, oil, geothermal energy extraction, and subsurface material storage. The key challenge is to balance the protection and use of groundwater for drinking purposes with the space needed for mining activities related to energy supply (*Structuurvisie Ondergrond*, 2018).

The Vision aims to clarify the national government's approach to decision-making concerning developments in drinking water and energy supply. It provides guidance and considerations for decision-making across various scales (*Structuurvisie Ondergrond*, 2018). Within this framework, the national government only makes policy decisions regarding the approval or prohibition of activities in specific areas when necessary for issues of national importance.

The Vision complements existing regulations by establishing a framework for evaluating mining activities. Insights from this Vision directly or indirectly influence the issuance of environmental permits under the General Environmental Law (Wet algemene bepalingen omgevingsrecht) and are considered when granting exploration, extraction, and storage licenses under the Mining Act. As a result, the government proactively identifies regions where specific mining activities will be prohibited.

4.3. Qualitative analysis of visualized networks

The diagrams visualize the relationships between institutional statements within an action arena. These statements are derived from an analysis of policy documents. The following section is organized as follows: First, the institutional context is discussed, including what can be observed from the Institutional Network Diagram (IND), how it should be interpreted, and the main takeaways. Next, the institutional relations are detailed at both the component and institutional levels, focusing on the drivers behind the connections and the levels of institutions depicted in the diagram. The influence of the non-legally binding Subsurface Spatial Planning Vision on processes within the action arena is then described. Finally, the challenges and complexities in institutional dynamics are addressed.

4.3.1. Action arena 1: project initiation

Institutional context

Various formal institutions define procedural steps required to advance an UHS project. These steps include obtaining the necessary permits and submitting operational plans as shown in Figure 4.1 (van Gessel & Hajibeygi, 2023).

The initial step involves applying for exploration, extraction, and/or storage permits as mandated by the Mining Act. The specific permit required first depends on the project's scope. Typically, if salt caverns are already used for salt extraction, the exploration and extraction permits may already be in place. Once these permits are secured, the licensee must decide on the mining activities and submit exploration, extraction, and/or storage plans to the competent authority. These plans must detail the methods and technologies to be used. Additionally, an environmental permit is required for any mining activity under the General Environmental Law. The competent authority for these permits is the Minister of Economic Affairs and Climate Policy (hereafter: Minister). Once all necessary permits are granted and operational plans are approved, the project initiator may proceed with the UHS project.

Institutional relations

The process illustrated in the diagram pertains to the exploration permit and plan within the project initiation action arena. It is evident from the diagram that several actors are involved in the process. While the primary actors are the project developer and the competent authority, other stakeholders such as the municipality and the water board are also included.

One notable observation is the vague execution constraint *'within reasonable term'* in statement [1.4]. This constraint is unclear and does not provide specific guidance on what actors might expect. Additionally, the action arena appears to be quite participatory. Various institutional statements indicate the involvement of actors in the decision-making process, as seen in statements [1.4], [1.5], and [1.6]. However, the extent of their involvement and the timelines associated with it remain unclear. The diagram suggests a cascading relationship where the competent authority engages the provincial executive, who, in turn, must involve both the municipality and the water board.

Furthermore, although the action arena involves several steps that the project developer must navigate, the diagrams reveal that the competent authority holds the dominant position. The competent authority plays multiple roles throughout the process: establishing frameworks and guidelines, assessing and issuing permits (as seen in statements [1.7], [1.8], [1.14]), and ensuring transparency by disseminating information to the public and interested stakeholders (as indicated in statements [1.2] and [1.9]). This central role of the competent authority underscores the significant influence in both decision-making and regulatory oversight.

Lastly, the diagrams indicate that the action arena is predominantly regulated by Acts, with only one institutional statement derived from a Decree (statement [1.10]). This reliance on Acts signifies that the action arena is governed by a robust legislative framework, where rules are established through formal legislative processes involving debate and approval by a representative body (Carey & Shugart, 1998). Acts are generally more stable and rigid compared to Decrees, providing long-term stability and reducing the likelihood of changes in the institutional environment (Ramkema et al., 2008).

Influence of the Subsurface Spatial Planning Vision

Considerations and policy implications from the structural vision indirectly affect the assessment and issuance of environmental permits and are considered when granting exploration, extraction, and storage permits. The structural vision also outlines the planned use and management of the subsurface, specifying areas designated for particular preferred activities. Although these regulations regarding subsurface use and management may not be codified in legal documents, they are taken into account during the permit application evaluation process.

Thus, while the Vision does not directly impact the institutional environment of the action arena, its influence is more indirect and strategic. The conclusions and mandates presented in the Vision shape the decisions and actions of various actors, guiding them at a higher, strategic level.

Challenges in institutional dynamics

Within the first action arena, no challenges in terms of conflicts and voids have been identified.

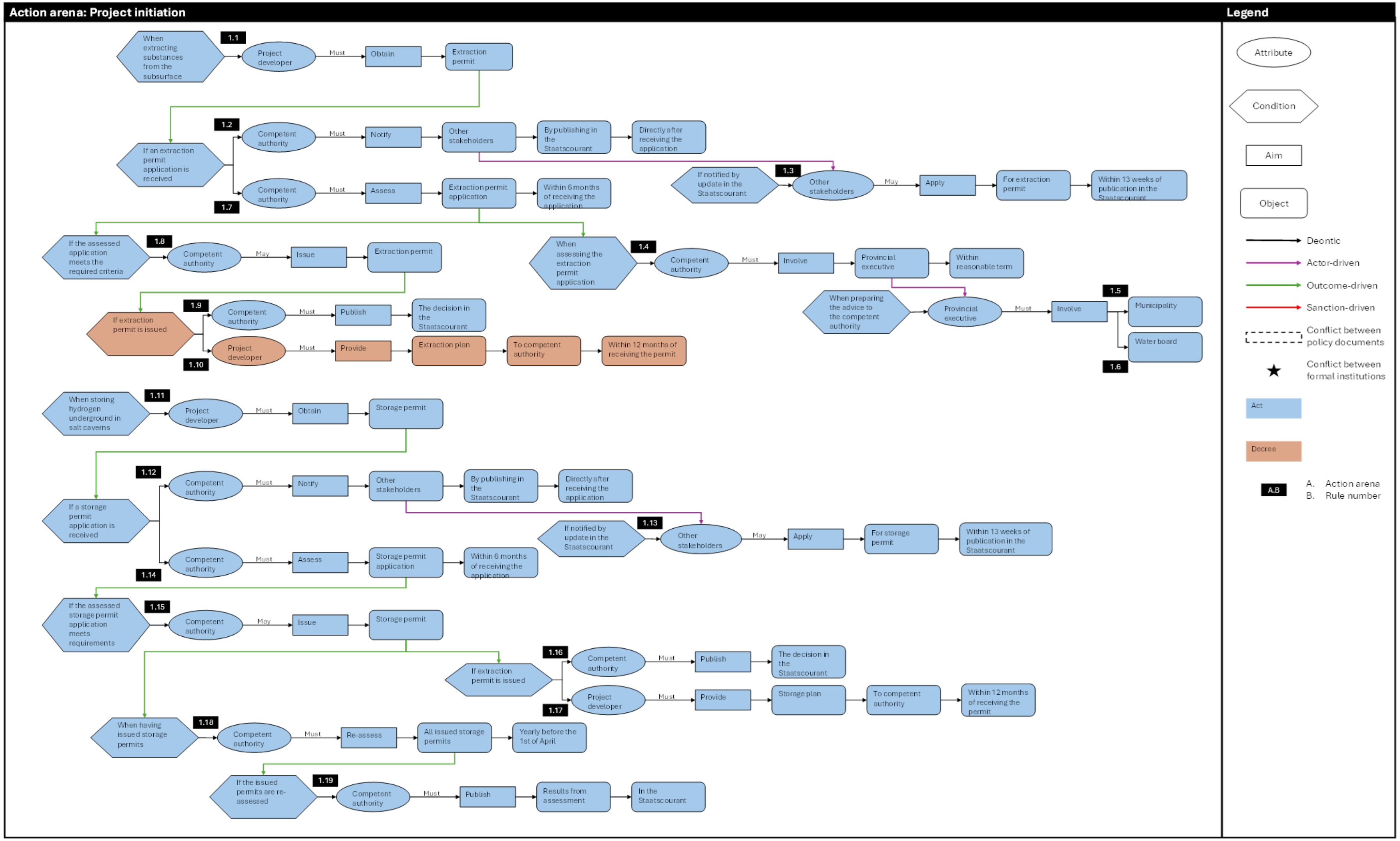

Figure 4.1: IND for action arena 1

4.3.2. Action arena 2: community and stakeholder engagement

Once project initiators have received the required permits and the operational plans are approved, involving the local communities and stakeholders becomes essential. The IND is presented in Figure 4.2.

Institutional context

The Environment and Planning Act outlines how the Minister collaborates with all stakeholders in large energy projects, specifying how local community input should be integrated into the decision-making process. This is guided by five key principles for stakeholder and community participation: (i) uniting stakeholders, (ii) early involvement of the community, (iii) transparency and trust, (iv) collective responsibility in environmental participation, and (v) tailored engagement (*Structuurvisie Ondergrond*, 2018; Winters et al., 2020). Central to this participatory approach is the collaboration between the competent authority, project initiators, and stakeholders, including citizens, businesses, local governments, and societal organizations. Early involvement allows these stakeholders to propose alternative approaches and solutions to the issues at hand.

The Environment and Planning Act mandates this participatory approach throughout the project procedure and decision-making (Winters et al., 2020). The project procedure consists of four steps: (i) notification of intention, (ii) notification of participation, (iii) exploration, and (iv) preference decision. The competent authority begins the project procedure by announcing the intent to explore the potential execution of an UHS project. A key responsibility of the competent authority is to determine whether a preferential decision is required, allowing third-party stakeholders to propose solutions to the problem the project aims to address.

In the notification of participation step, the competent authority outlines who can participate, when, and how, as well as defining the roles of the competent authority and project initiator in the participation process. During the exploration phase, the competent authority gathers information about the project, its physical environment, and potential solutions to the problem it aims to solve. Finally, the project decision describes how the community and stakeholders are involved in the decision-making preparations, ensuring that the interests of all stakeholders are considered equally.

Institutional relations

The IND mapping reveals that the judgment of whether a project results in significant harmful environmental effects acts as a bottleneck, as indicated in statement [2.6]. This bottleneck occurs because numerous institutional responses depend on this determination, connected by an outcome-driven link. This connection highlights that the aim—assessing whether the project leads to environmental effects—is tied to the execution constraints of various institutional statements, such as statements [2.7], [2.8], [2.9], and [2.10]. If the assessment indicates that the project could lead to significant environmental effects, additional actors become involved in the decision-making process related to the environmental permit application. These stakeholders, including the municipality, provincial executives, and the water board, may impose further constraints and requests, potentially prolonging and complicating the process for the project developer.

Additionally, the statements in the IND are predominantly connected through outcome-driven connections. This structure creates a cascading sequence of processes within the action arena, where the outcome of one statement triggers the activation of another. As a result, there are no conflicts at the institutional statement level, as the sequential flow facilitates a smooth transition between actions and decisions.

Influence of the Subsurface Spatial Planning Vision

The Vision addresses the concerns of local communities and stakeholders regarding the safety of subsurface hydrogen storage and the exploitation of salt caverns. It emphasizes the need for sustainable, safe, and efficient use of the subsurface.

Sustainability and efficiency are particularly relevant in the context of UHS, where safety is extensively regulated by the Mining Act. The Vision defines sustainability as the responsible use of resources and careful management of finite inventories. Efficiency is described as the optimal use of subsurface space, ensuring that the limited available area is utilized effectively (*Structuurvisie Ondergrond*, 2018). Specifically, the Vision mandates that activities such as UHS should be conducted in locations where natural conditions are most suitable, such as salt caverns. These activities are prioritized in such settings due to their specific properties, making them more suitable than other potential locations.

The mandates outlined in the Vision influence formal rules and regulations as specified in the analysed policy documents. This influence is reflected in the IND, where a conflict between the Vision and formal rules is indicated by a dashed box surrounding the relevant institutional statements. This conflict is further discussed below as a challenge in the institutional dynamics.

Challenges in institutional dynamics

An interesting aspect of the INDs is the identification of institutional voids. These voids, as previously defined, refer to gaps in the network or missing information that result in institutions failing to support functioning markets (Dieleman et al., 2022).

In the analysis, statement [2.15] requires project developers to include a participation plan and mandates that the competent authority involve various industry experts in decision-making processes, as detailed in statements [2.7], [2.8], [2.9], and [2.10]. However, the policy documents do not provide concrete guidelines on how third parties should be incorporated into the decision-making process or specify how much of their input should be reflected in the outcomes. The criteria for inclusion are unclear, as are the sanctions for failing to meet these criteria. Consequently, the extent of participation is somewhat left to the discretion of the market.

On one hand, this ambiguity might be intentional on the part of policymakers. Allowing flexibility in the participation process can enable it to be adapted to local contexts, encouraging project initiators to carefully design their processes. Given that the Environment and Planning Act covers a broad range of projects, flexibility in certain processes can be advantageous. On the other hand, the lack of clear guidelines can lead to inconsistent interpretations and ambiguity regarding desired outcomes. This ambiguity may compromise the quality of the process, as it heavily depends on the expertise of the competent authority and the project initiator. New players, in particular, might struggle with devising a participation strategy without clear standards for what constitutes sufficient participation and how it is assessed.

Both project developers and the competent authority must navigate the balance between environmental interests and stakeholder participation during the development of an UHS facility. In situations of uncertainty regarding restrictions, expectations, and requirements for stakeholder participation, clear guidance is needed. However, the absence of such guidance represents an institutional void. This void arises when general regulations are established at a high level but lack specific details, making the regulations broadly applicable while leaving companies and organizations inexperienced in participatory processes without adequate direction.

A second insight from the INDs is the identification of an institutional conflict. As previously noted, the participation process requirements mandated by the Environment and Planning Act allow for some interpretation. Specifically, the Act requires that local communities must be involved in decision-making processes from an early stage. For example, the competent authority must enable local communities and stakeholders to propose alternative solutions to the problems a project aims to address, as indicated in statements [2.2] and [2.3]. However, several issues arise with this requirement.

Firstly, while third parties may propose alternative solutions, the scope of these solutions is heavily dependent on how the problem is defined. For instance, in the context of an UHS project, is the problem framed as reducing greenhouse gas emissions, or addressing the variability of renewable energy sources? Furthermore, the extent to which viable alternative solutions exist for large-scale subsurface hydrogen storage remains unclear. The initiative to propose alternatives rests with the market, yet the site location and type of storage are predetermined for the project developer. Developers typically focus on specific projects and are less likely to develop entirely different solutions to address a broader issue, such as contributing to national climate targets.

Secondly, to accommodate project developers, the Dutch government has introduced the Vision. As discussed in section 4.2, the Vision outlines structural policies for activities of national importance and establishes a framework for evaluating mining activities, which significantly affects the issuance of permits. The Vision designates certain areas as highly suitable for UHS projects, stating that areas with optimal natural conditions for specific activities, like UHS in salt caverns, are prioritized over other activities. Consequently, this framework can limit the ability of third parties to propose alternative solutions, as the Dutch government effectively pre-selects the most suitable solutions for specific areas.

This creates a notable conflict between institutional levels. While the Environment and Planning Act emphasizes the importance of third-party participation, the Vision restricts possibilities by designating preferred solutions for certain areas, thereby limiting the scope for alternative proposals.

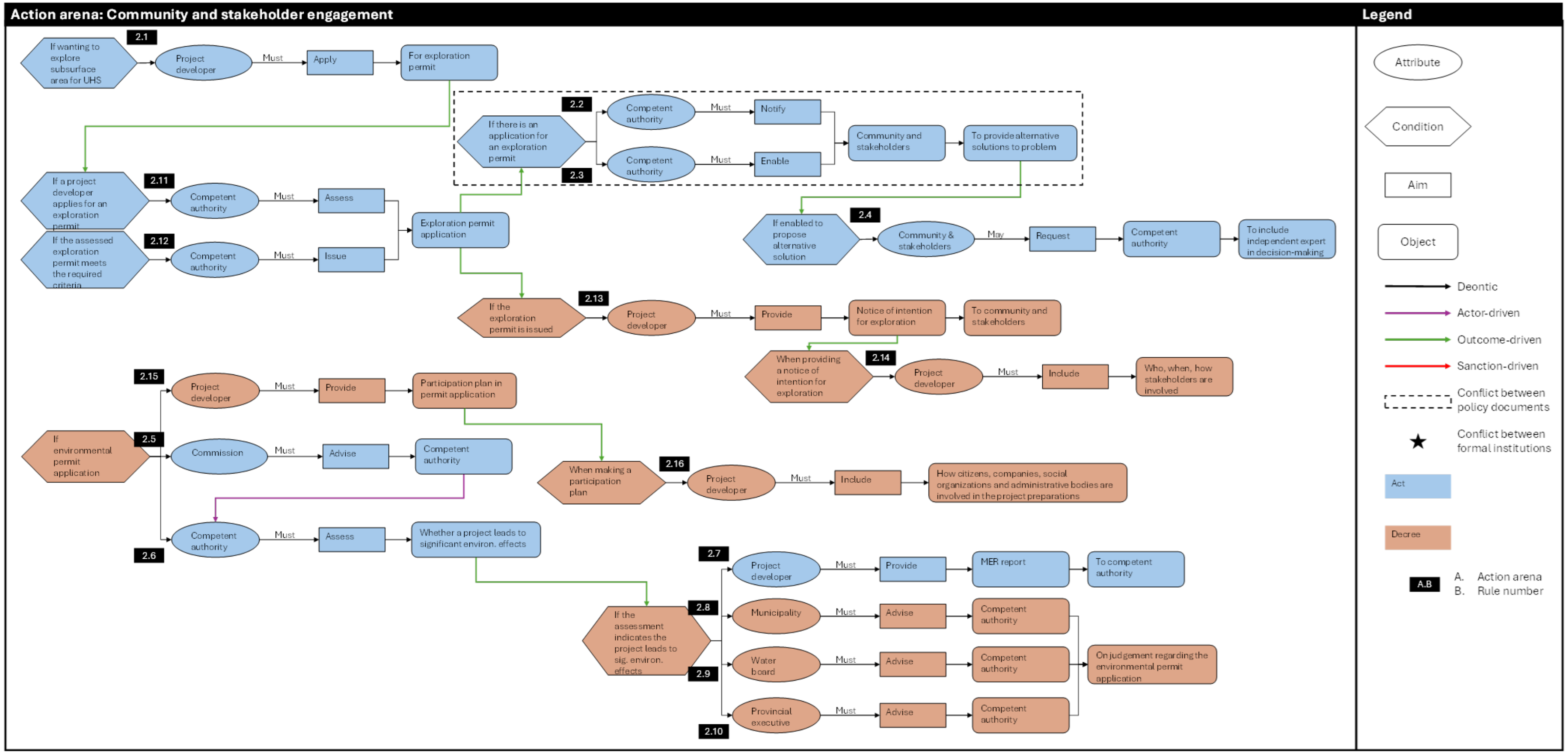

Figure 4.2: IND for action arena 2

4.3.3. Action arena 3: closure, safety, and subsidence control

Institutional context

Within the action arena, a project initiator must navigate various plans, analyses, and assessments. Consequently, the action arena is divided into two INDs related to these processes.

First, the safe closure of a UHS facility involves a comprehensive process, beginning with the submission of a closure plan to the competent authority, as illustrated in Figure 4.3. This closure plan includes a Seismic Risk Analysis (SRA), required to identify safety risks associated with seismic activities. The SRA is reviewed by the State Supervision of Mines (SodM) to ensure compliance with safety regulations and to mitigate potential hazards.

Second, the safe management and operation of the UHS project require adherence to a measurement plan, as mandated by the Mining Act, shown in Figure 4.4. This plan entails monitoring potential ground movements related to UHS activities. The management of these measurements involves documenting the results and discussing them with the competent authority. Additionally, a disaster response plan must be developed for each mining installation. This plan includes a worst-case assessment to evaluate the likelihood of earthquakes, factoring in the expected magnitude and depth of earthquakes along with the presence of above-ground infrastructure.

The competent authority holds the power to fully or partially deny a permit based on safety concerns. This underscores the critical role of the action arena in determining whether a project initiator can proceed with developing a UHS facility.

Institutional relations

The first IND illustrates the institutional statements related to the closure of a UHS facility. It reveals that the relationships between institutions follow a sequential process. The formal institutions outline the steps necessary for the safe abandonment of the facility after closure. The IND shows no institutional relationships leading to undesired or unexpected outcomes. Instead, the analysis highlights a close collaboration between the project developer and the competent authority, suggesting a well-coordinated and structured process.

The second diagram addresses the measurement and disaster response plans. Here, the formal institutions also follow a procedural nature. The sequential institutional statements create a clear, predictable process. This diagram shows a dependency between institutional statements, denoted by outcome-driven connections. Specifically, the connection between the [B] Object of statement [3.11] and the [C] Activation constraints of subsequent statements [3.12], [3.13], and [3.14] illustrates that once the measurement plan is approved, it triggers a cascading process. This process requires the project developer to update, execute, and provide information to various stakeholders within specified timelines.

Both INDs are dominated by outcome-driven connections, emphasizing the importance of effective and efficient communication and collaboration. Ambiguities in responsibilities and communication channels between actors can potentially lead to bottlenecks.

An interesting observation from the diagrams is the various roles and responsibilities of the competent authority throughout the entire process. The competent authority is involved in assessing various plans and reports, playing a critical role in determining whether a project may proceed, as seen in statements [3.3], [3.6], and [3.11]. Additionally, the competent authority is responsible for disseminating information to stakeholders to ensure transparency and foster engagement, as indicated in statements [3.8] and [3.18]. This includes updating the Staatscourant with decisions and publishing results from monitoring activities, as noted in statement [3.17].

Influence of the Subsurface Spatial Planning Vision

The Vision does not specifically address safety requirements for mining activities. Rather, it focuses on policy choices concerning the desirability of permitting or excluding activities in certain areas, especially when these activities pertain to matters of national importance. As a result, this research has found no direct influence of the Vision on the formal institutional statement derived from the analysed policy documents.

Challenges in institutional dynamics

Within the third action arena, no challenges in terms of conflicts and voids have been identified.

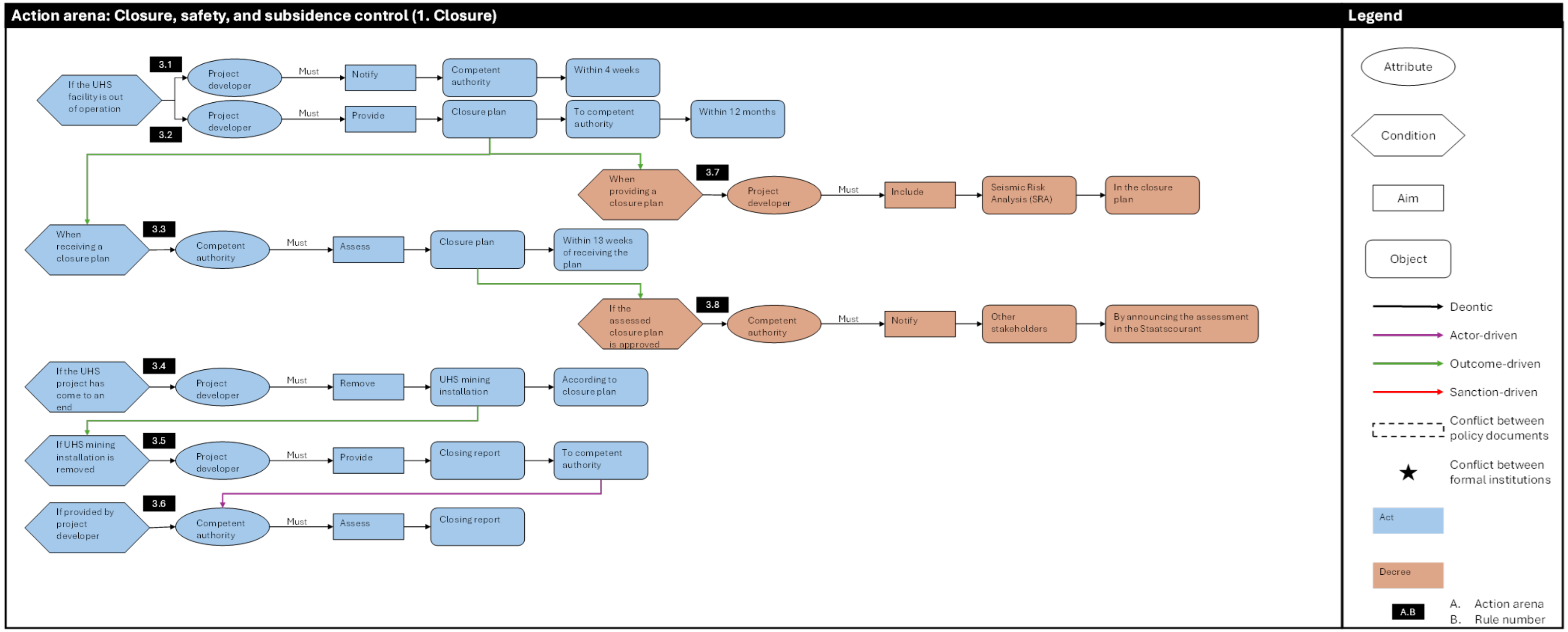

Figure 4.3: IND for action arena 3(1)

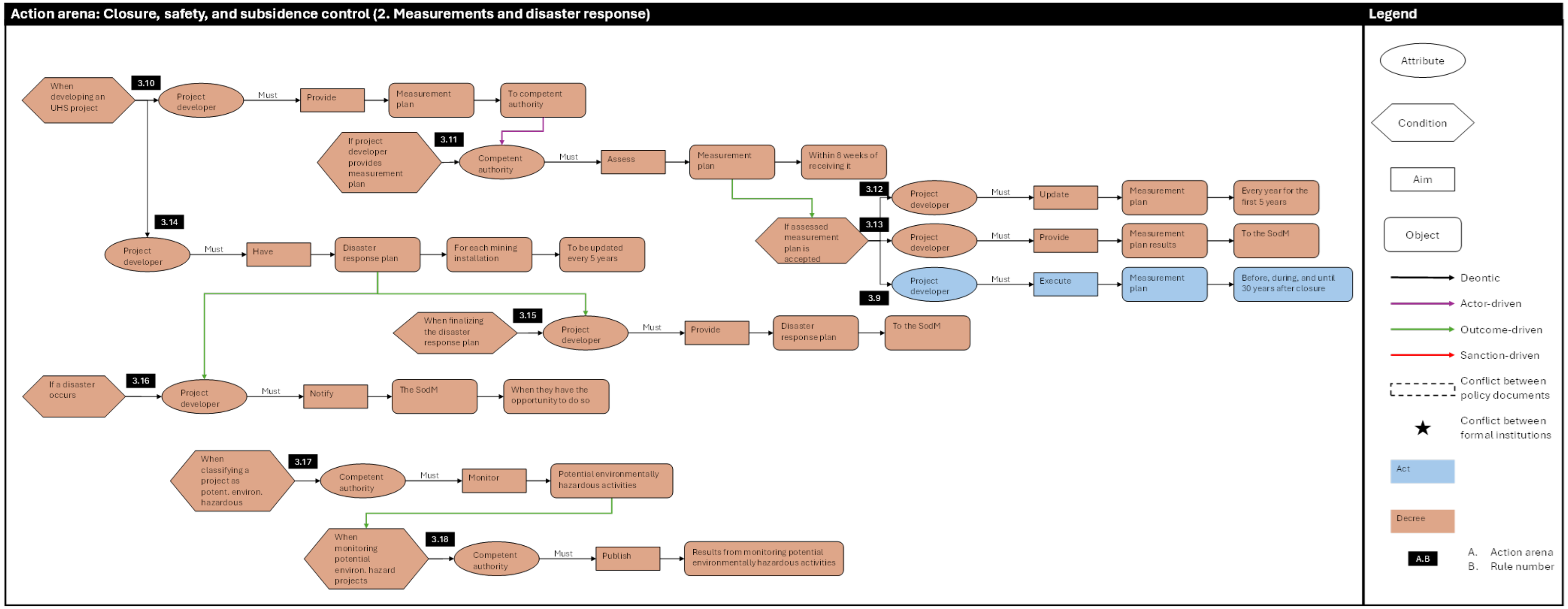

Figure 4.4: IND for action arena 3(2)

4.4. Quantitative analysis of visualized networks

Within this section, the network diagrams as presented and discussed in the previous paragraph are analysed using quantitative measures. The quantitative analysis includes the discussion of the dominant attributes and various network metrics. A complete overview of the calculations can be found in Appendix C.

4.4.1. Dominant attributes in the institutional context

When analysing the formalized institutions and action arenas, it becomes clear that the action arenas encompass eight distinct attributes, each varying in importance depending on the specific context. The analysis underscores the dominance of two key attributes: the competent authority, referenced in 22 institutional statements (42%), and the project developer, mentioned in 21 statements (40%). This indicates that these two attributes play a crucial role in the institutional framework governing the action arenas, highlighting their centrality and influence.

The extensive involvement of these attributes, particularly the competent authority, introduces potential conflicts. The competent authority, specifically the Minister of Economic Affairs and Climate Policy in the context of UHS in salt caverns, plays a critical role in both the duration and quality of permitting procedures and participation processes. The Minister is the competent authority across all the analysed policy documents and thus bears significant responsibilities. This includes addressing and issuing permit applications and operational plans, as well as involving various industry experts in the decision-making process.

Moreover, the Minister also has broader responsibilities as a policymaker and coordinator throughout different phases of project development. This multifaceted role can lead to conflicts of interest and challenges in balancing responsibilities effectively and transparently. For example, while the Minister must ensure thorough and unbiased assessment processes, there may be pressures related to policy goals or industry interests that could influence assessments and the inclusion of industry experts in the decision-making process. The simultaneous need to act as a regulator, facilitator, and policymaker introduces complexities in achieving transparent and fair outcomes.

This scenario highlights the importance of clear institutional guidelines and checks to mitigate potential conflicts in roles and responsibilities. The competent authority must fulfil its roles without compromising the integrity of the process or creating distrust among third parties.

4.4.2. Centrality of Attributes

In this research context, centrality refers to the ease of communication related to an actor. An attribute with a high centrality score plays a crucial role in determining the actions taken and the outcomes achieved. Actors with high centrality scores are thus seen as key influencers within a specific action arena. A centrality measure below 1 is considered low.

The main insight from measuring the centrality of attributes is the high centrality of both the competent authority, with an average score of 1.7, and the project developer, with an average score of 1.6. Notably, the second action arena shows especially high centrality measures for both attributes: 2.2 for the competent authority and 2.6 for the project developer. Across all action arenas, both attributes consistently score above 1. This is expected, as these attributes play critical roles: the competent authority ensures compliance with rules and regulations, while the project developer drives the processes within the action arenas.

High centrality scores suggest efficient coordination and a clear division of roles and responsibilities. However, they also imply that a small group of actors predominantly decides the course of action in the arena.

4.4.3. Embeddedness of objects

Embeddedness is rated on a scale from 0 to 1. An object with low embeddedness indicates that few institutions rely on it for their execution. Conversely, an embeddedness score close to 1 signifies that many institutions depend on the object. In this research context, embeddedness measures the extent to which actors share responsibility for achieving a specific outcome or object.

In this study, several direct objects exhibit a high embeddedness score of 1. These objects primarily pertain to the various permits that project developers must acquire, as well as the operational plans and reports they must submit. The high embeddedness score of these permits and plans underscores their critical importance, as they are prerequisites for advancing to subsequent development phases. This score indicates that other institutions rely heavily on the successful attainment of these objects. Consequently, it can be argued that various actors have a significant interest in these permits and plans, and their behavior is influenced by outcomes such as the approval or denial of permit applications.

4.4.4. Density of objects

The density of an object, similar to its embeddedness, is rated on a scale from 0 to 1. A score close to 1 indicates that a significant number of institutions depend on the execution of other institutions for their own functioning.

In this study, the second and third action arenas show average density scores, both close to 0.5. These results suggest that a moderate number of institutions rely on the execution of other institutions for their own operations. In contrast, the first action arena has a relatively low density score of 0.26. This low density indicates a diverse range of practices among actors within the network and limited information exchange. This finding can be attributed to the isolated processes involved in the application, assessment, and dissemination of information.

4.5. Connecting action arenas

Each action arena is depicted as a separate stage; however, they are intricately linked, as shown in Figure 4.5. The project initiation phase is the first step in the development of a UHS project. Yet, as revealed by the INDs, participation plays a crucial role in this phase, similar to its role in the second action arena. Furthermore, the final action arena—covering closure, safety, and subsidence control—requires the submission of a closure plan. Although the closure plan pertains to the safe abandonment of the UHS facility, it must be submitted as part of the operational plans in the project initiation arena to secure the necessary permits. This highlights the interconnectivity between the action arenas. Rather than functioning as distinct phases, the arenas operate in parallel throughout the project's development.

Recognizing these interconnections between INDs is crucial, as decision-making processes and outcomes in one action arena can influence behaviours and actions in another. For example, in the second action arena, if communities and stakeholders raise safety concerns through the participatory process or protests, the provincial executive may impose additional stringent regulations. These regulations would need to be incorporated into the operational plans submitted in the project initiation arena. Overall, the separation of the action arenas is not as distinct as the analysis might suggest. These arenas are interconnected and influence each other through feedback loops.

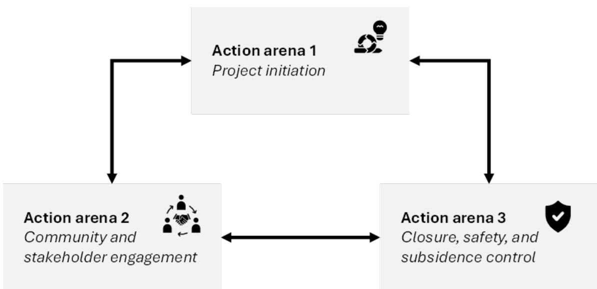

Figure 4.5: Links between the action arenas

4.6. Rule typology analysis

4.6.1. Qualitative analysis

The qualitative analysis focuses on discussing each rule type. For each rule type, the analysis addresses its presence in the action arenas, the related aims and examples of institutional statements found in the context. It is important to note that the rules types are assigned based on the author's understanding. Some institutional statements may fit into multiple rule types; in such cases, the final categorization is determined by the author's judgement and precautionary steps, as detailed in subsection 3.4.1. An overview of the rule typologies per action arena is given in Figure 4.6.

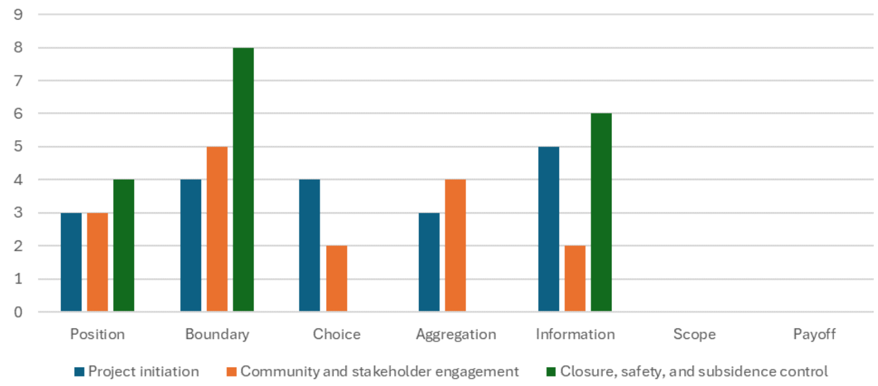

Figure 4.6: Overview of the number of rule typologies per action arena

Position rules

A total of 10 position rules were identified across the first and third action arenas, with the majority (4) found in the third arena: closure, safety, and subsidence control. In this phase, position rules define the roles and responsibilities of key actors, such as the Minister of Economic Affairs and Climate (hereafter referred to as the Minister). These rules specify which actors are accountable for particular decisions or assessments. For example, statement [1.18] mandates that the Minister is required to reassess all granted storage permits annually to determine whether the area covered by a permit should be reduced. The objectives that regulate these rules involve actions such as *enforce*, *assess*, and *decide*. Therefore, the identified position rules establish the administrative and decision-making tasks of specific actors within this context.

Boundary rules

The analysis revealed that the selected action arenas contain 17 boundary rules, making this the most prevalent rule type. Of these, eight boundary rules were identified in the third action arena: closure, safety, and subsidence control. These rules explicitly govern the actions that project developers must undertake and the restrictions placed on those actions. For instance, statement [3.9] mandates that the project developer must implement a measurement plan before, during, and for 30 years after closure, covering safety, earthquake, and subsidence monitoring.

The first action arena, project initiation, contains four boundary rules, which include institutional statements regulating the requirement to obtain specific permits and submit operational plans. Only individuals or entities with the necessary permits are authorized to initiate a UHS project. The second action arena, community and stakeholder engagement, also contains four boundary rules, one of which requires the project developer to submit an Environmental Impact Report (Milieueffectrapportage, MER) to the Minister.

In summary, boundary rules outline the procedures, conditions, terms, and criteria that govern how actors enter or exit their roles within the context.

Choice rules

The action arenas in the research context contain a total of six choice rules. These rules specify the actions that certain actors *may* take within an action arena. In the project initiation arena, choice rules relate to the competent authority's power to grant or deny an application, or to approve or reject an operational plan. Decision-making under these rules involves actions such as *apply, deny, issue* and *decide*, which allocate authority to actors for making key decisions within the process.

Information rules

The analysis identified 13 information rules that govern the availability and sharing of information among actors. These rules indicate a structured approach to information dissemination and transparency (Lai & Zhao, 2023). Information rules reflect actions such as *update, provide*, and *publish*, regulating the submission and receipt of specific data, such as measurement results or assessment outcomes. Typically, these rules specify both the sender and the recipient of the information.

In the third action arena — closure, safety, and subsidence control — five information rules were identified. For example, statment [3.16] mandates that the project developer must notify the State Supervision of the Mines (Staatstoezicht op de Mijnen, SodM) as soon as possible if a disaster occurs. Additionally, other rules regulate the notification procedures for planned UHS activities. Across all action arenas, information rules establish the procedures and platforms for publishing, notifying, and announcing updates related to subsurface activities. For example, in the first and third action arena, the Minister is required to update the Staatscourant, a governmental newspaper, whenever permit applications are approved (see statements [1.19] and [3.8]).

Aggregation rules

The analysis identified a total of seven aggregation rules across the three action arenas, with most (four) found in the second action arena. In the examined institutional context, aggregation rules play a critical role in determining how decisions are made collectively by specifying how actors contribute to the decision-making process (Crawford & Ostrom, 1995). These rules outline the processes for participation, stakeholder engagement, and the integration of inputs into a final decision, ensuring that decision-making is inclusive and structured.

Aggregation rules are particularly prominent in the second action arena — community and stakeholder engagement — where joint decision-making is central to the process. For example, this arena mandates that the municipality, water board, and provincial executive must advise the competent authority on various decisions (see statements [2.8], [2.9], and [2.10]). Interestingly, the first action arena, project initiation, also contains several aggregation rules, suggesting that significant participatory efforts are required in this phase as well. Here, multiple stakeholders are involved in advising the competent authority, reflecting the need for collaborative decision-making early in the project development process (see [1.4], [1.5], and [1.6]).

Aggregation rules shape joint decision-making efforts and often reflect aims such as *advise* or *involve*. The absence or limited presence of aggregation rules can create uncertainty regarding whose input is considered and how that input will influence the final decision.

Scope rules

Surprisingly, the analysis reveals the absence of any scope rules within the institutional environment. Scope rules define the boundaries and outcomes of actions within an institutional framework (Crawford & Ostrom, 1995). These rules clarify the limits of authority and responsibility for actors. Without scope rules, there may be ambiguity about the jurisdiction and authority of different actors.

For instance, in each action arena, the Minister serves as the competent authority for numerous processes, including deciding on permit applications, reviewing operational plans, and enforcing sanctions. Furthermore, the Minister holds this role throughout the entire lifecycle of a UHS project. The concentration of 'power' in the hands of the competent authority, without the constraints typically imposed by scope rules, could lead to uncertainty and potential trust issues among other stakeholders.

Payoff rules

Additionally, beyond the absence of scope rules, the analysis reveals that no payoff rules are captured in the action arenas. Payoff rules define the rewards or sanctions associated with specific actions or outcomes (Crawford & Ostrom, 1995). These rules establish the incentives and penalties that shape actor behaviour.

In particular, payoff rules are expected to play a crucial role in the third action arena — closure, safety, and subsidence control — given the potential severe consequences of non-compliance with safety regulations, especially considering the flammable and toxic nature of hydrogen. As environmental and operational safety are critical concerns in large-scale energy projects, payoff rules could be instrumental in outlining sanctions for non-compliance with safety regulations, while also ensuring accountability among stakeholders. The absence of such rules might lead to uncertainty in enforcement and a lack of clear consequences for violations, potentially undermining safety standards.

4.6.2. Quantitative analysis

Based on the identified rule typologies, the composition of the rules is analysed to identify the features of the institutional structure of UHS in salt cavern's across the different action situations. Overall, this research study identified 53 rules across the three action situations (see Figure 4.10), taken from four policy documents: Mining Act & Decree, and the Environment and Planning Act & Decree.

Action arena 1: project initiation

The composition of rule types varies significantly across the action arenas, reflecting their unique institutional characteristics. In the first action arena, project initiation, 19 rules have been identified, making it the most rule-dense arena. This arena is dominated by choice and information rules, as illustrated in Figure 4.7. Notably, it has the highest concentration of choice rules compared to other arenas.

Information rules in this arena regulate the flow of information from the project initiator and the competent authority to third parties, including local communities, other developers, and municipalities. These rules also dictate the procedures for notifying stakeholders about project developments and updates, particularly regarding the availability of information throughout the project phases. For instance, statement [1.16] mandates that the competent authority must publish updates in the Staatscourant, a governmental newspaper, whenever a decision about a permit or operational plan is made. These information rules help ensure transparency during the project initiation phase, keeping all relevant stakeholders informed.

Furthermore, choice rules in this arena pertain to the decision-making process of the competent authority. Actors looking to develop UHS projects in salt caverns must secure the necessary permits from the competent authority and submit operational plans for approval before proceeding. The competent authority is responsible for deciding whether to grant or deny these permits and operational plans, giving it significant influence over the course of the project.

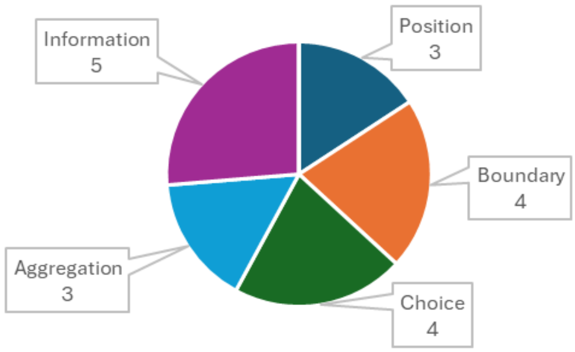

Figure 4.7: Project initiation = 19 institutional statements

Action arena 2: community and stakeholder engagement

The second action arena, which focuses on community and stakeholder engagement, contains 16 rules, making it the smallest of the action arenas. The majority of these rules are aggregation and boundary rules, followed by position, choice, and information rules, as depicted in Figure 4.8. Notably, this action arena has the highest concentration of aggregation rules compared to the others, which reflects the administrative and participatory nature of the processes it governs, as well as the roles of the actors involved in decision-making.

For actors intending to develop UHS projects in salt caverns, participation from various stakeholders is mandatory. This participatory process requires the involvement of municipalities, provincial executives, and the water board in certain decision-making processes. However, while these actors are formally included in the process, the rules do not clearly define the extent of their contributions. The competent authority is required to seek advice from these entities, but the specific methods of their involvement are not explicitly formulated.

Interestingly, given that this action arena deals with the participatory processes involving local communities, one would expect a high number of aggregation rules detailing how and when these communities should be included in decision-making. However, the analysis shows that local community involvement is primarily regulated through information provision. The precise nature of this involvement—such as its extent, the manner in which it should occur, and its timing—is not clearly specified, allowing for flexibility and leaving room for interpretation based on the particular situation.

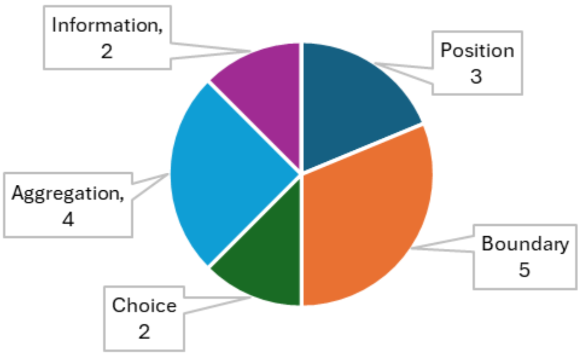

Figure 4.8: Community and stakeholder engagement = 16 institutional statements

Action arena 3: closure, safety, and subsidence control

The third action arena contains 18 rules, as depicted in Figure 4.9. A key observation from the figure is that only three rule types are present in this arena: position, boundary, and information rules. Moreover, this action arena has the highest concentration of boundary rules compared to the others. These boundary rules focus on the minimum safety requirements that the project initiator must meet to comply with national regulations. They include the submission of essential plans such as measurement plans, closure plans, and disaster response plans, along with specific assessments like the Seismic Risk Analysis. The analysis reveals that the competent authority holds primary responsibility for approving these plans.

Information rules in this action arena primarily regulate the notification procedures for emergencies. However, there is a notable absence of aggregation rules, which typically govern the involvement of additional actors in decision-making processes. For example, while actors like the State Supervision of Mines (SodM) and the Mining Council are involved in other action arenas, they are not included in this one. This absence of aggregation rules is significant because aggregation rules ensure participatory decision-making processes in other arenas. Without them, this action arena operates under a more centralized decision-making model, potentially limiting the involvement of other stakeholders in crucial safety-related decisions.

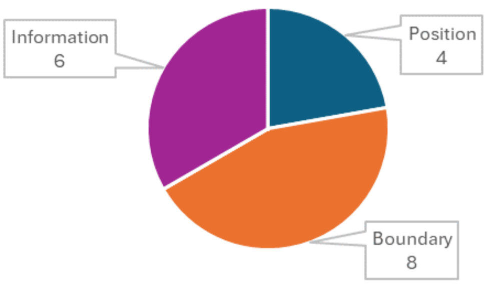

Figure 4.9: Closure, safety, and subsidence control = 18 institutional statements

Combined action arenas

Overall, the analysis reveals a consistent institutional pattern across the action arenas, marked by the prevalent presence of boundary, information, and position rules. As illustrated in Figure 4.10, boundary rules are the dominant rule type, followed by information rules. This pattern suggests that the institutional framework emphasizes both the regulatory aspects of access and exit from the institutional context and the dissemination of information to third parties. The prominence of boundary rules implies stringent regulations regarding entry and exit, ensuring that only qualified and authorized actors participate in specific activities. These rules include detailed procedures for obtaining permits and submitting operational plans, which help maintain high standards of competence and reliability among stakeholders.

Additionally, the focus on information rules highlights the importance of managing the flow of information, specifying who shares what information and how it is communicated between actors. Effective information management is crucial for maintaining transparency and supporting informed governance (Casalino et al., 2015). The established protocols for information sharing are designed to ensure that relevant data is readily accessible to stakeholders.

The emphasis on boundary and information rules, coupled with a limited presence of aggregation rules, indicates a lack of collective decision-making in UHS project development. While there are guidelines for participation and information dissemination, the extent of stakeholder involvement in decision-making processes is not clearly defined.

Furthermore, the absence of scope and payoff rules is noteworthy. The lack of scope rules suggests that the boundaries of possible outcomes are not clearly defined. Similarly, the absence of payoff rules is consistent with the assumptions outlined in section 4.1. Generally, payoff rules pertain to sanctions, penalties, or rewards, often detailed by an [O] Or else component. However, the formal institutions analysed are derived from policy documents at the Dutch national level, which are interpreted as formal rules with obligatory responsibilities rather than explicit sanctions. Consequently, the analysed statements do not explicitly delineate payoff rules. Additionally, as the classification of institutional statements was performed by a single individual, there is an objective element in the analysis, with some statements potentially fitting multiple rule types. In such cases, decisions were made to classify these statements under alternative rule types rather than as payoff rules.

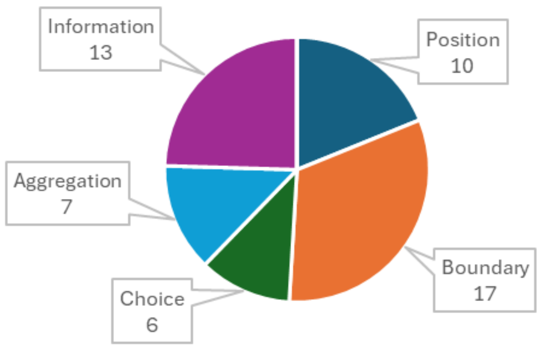

Figure 4.10: Total of combined action arenas = 53 institutional statements

4.7. Recommendations for improving the institutional environment

Based on the analysis and the provided analytical insights, this study provides several recommendations to explore for policymakers and involved actors.

Addressing the institutional conflict

Within the analysis, one institutional conflict is identified in the second action arena: community and stakeholder engagement. The conflict relates to the different levels and hierarchies of policy documents. As UHS projects contribute to the decarbonization of the future energy mix, and it therefore considered of national importance, it is subject to extensive regulation across various policy documents (Weymouth

& Hartz-Karp, 2019). While the Environment and Planning Act acknowledges this significance, it may inadvertently raise high expectations among third parties, such as local communities, about their role and influence in such projects. In practice, however, as decisions regarding necessity and alternatives are made in documents like the Vision, the extent of their participation is often limited.

Therefore, this study recommends that large-scale energy projects, such as UHS, be integrated not only into the national vision but also into local energy policies and environmental plans. By empowering local governments to develop policies and plans related to UHS, local communities and stakeholders will have a better opportunity to engage in discussions about the role of UHS in their immediate environment. Facilitating a dialogue between national and local representatives helps manage the expectations of local third parties. Moreover, effective communication about the involvement of these third parties can help eliminate false expectations and enable local communities and stakeholders to focus on relevant processes (Hazemba & Halog, 2021).

Improving participatory processes

The research reveals that there is ambiguity regarding the participatory processes and strategies within the institutional context. The analysis indicates that there is limited counsel regarding the division and assessment of participation strategies. Especially, actors with limited experience in this field might run in to difficulties. Given that there is in general limited experience with hydrogen, and especially UHS in the Netherlands, it can be argued that this might be the case for all the actors involved.

To relieve some of this ambiguity, a general improvement relates to the provision of extra guidance regarding the participation strategies. Establishing clear aggregation rules that define how stakeholders can participate in decision-making processes. By institutionalizing participation, the framework can better align with policy goals and encourage more collaborative project outcomes. Effective participation of stakeholders can enhance the quality of the participation plan, reduce resistance from local communities, and decrease uncertainty for project developers. Allowing stakeholders to voice their concerns and share information can foster greater trust and transparency in the project development process (Walker et al., 2010).

Actor roles and responsibilities

The research highlights the dominance of two attributes: the competent authority and the project initiator. Not only are these two actors referenced in practically all institutional statements (together 82%), but the centrality measurements underscore these findings by calculating the average scores, which are significantly high (both >1.5).

The rule typology analysis reveals there are currently no scope rules in the institutional environment. This aligns with the dominance of the attributes. Scope rules clarify the limits of authority and responsibility for actors, without which there may be ambiguity about the jurisdiction and authority of actors, leading to clearly dominant actors in an institutional context. Adding scope rules could address these issues by providing clear boundaries for each actor's role and responsibilities, thereby reducing overlaps and conflicts. By defining the scope within which each actor operates, these rules can mitigate the risk of power imbalances and ensure that responsibilities are distributed more equitably. This can also enhance transparency and accountability, as actors will have a clearer understanding of their own and others' jurisdictions. Consequently, incorporating scope rules can help balance the influence of dominant actors and foster a more structured and efficient institutional environment.

5

Discussion of research methodology and results

The research study delved into the institutional context of UHS in salt caverns in the Netherlands, providing insights into the conflicts and barriers to the developments. The following chapter first discusses and reflects upon the scope and generalization of the research findings in section 5.1 and the results and insights from the analysis in section 5.2. Consequently, section 5.3 reflects on the research methodology.

5.1. Applicability and generalization of research findings

The initial scope of this research was a case study centred on the salt caverns at Zuidwending in the north of the Netherlands. However, as the thesis evolved to focus on Dutch national legislation, the scope was broadened accordingly. Despite this adjustment, concerns persist about the generalizability of the results.

Firstly, the research assumes uniform application of regulations across all locations in the Netherlands. In reality, variations may occur at the provincial level. For instance, provincial executives could impose specific restrictions on large energy projects within their jurisdictions, and additional requirements may emerge from local community and stakeholder participation.

Additionally, Dutch rules and regulations are subject to change. The policy documents analysed in this study were reviewed and published in 2024. It is important to recognize that these acts and decrees may be modified or supplemented due to political decisions, feedback from market players, jurisprudence, or shifts in European legislation.

Although the findings of this study are specific to the Dutch context, they offer valuable insights for other countries facing similar energy policy challenges. The institutional analysis methodology used here can be adapted to examine UHS projects in different regulatory environments, offering comparative insights into how various institutional settings influence energy infrastructure developments. However, Dutch legislation and institutional structures may differ significantly from those in other countries, so the key findings and insights from this research may not be directly applicable elsewhere.

In conclusion, the results of this study should be viewed as an initial exploration of the institutional environment governing UHS in salt caverns in the Netherlands. Further research is required to refine these findings and ensure their robustness and completeness.

5.2. Reflecting on results and insights

5.2.1. Qualitative analysis of the network diagrams

The qualitative analysis of the network diagrams provided valuable insights into the institutional environment for UHS. It revealed that the regulatory framework is significantly influenced by Acts and Decrees, which shape the actions of key stakeholders. One of the most important findings is the identification of an institutional void and a conflict within the second action arena, indicating critical gaps in regulatory and procedural structures that may hinder the effective governance of UHS projects.

The examination of relationships between institutional statements in the network diagrams shed light on the interconnectedness and dependencies among actors, revealing both the strengths and vulnerabilities of the current system. These results highlight the need for more structured regulatory guidance, especially where institutional gaps were identified. Moreover, the misalignment between the goals as outlined in policy documents implicates the need for anchoring the policy goals in both national as local energy policies and environmental plans.

While the approach provided a thorough analysis, it is important to recognize that the diagrams were created by a single researcher, which could introduce bias. Cross-validation by multiple researchers would enhance the robustness of these findings. Nevertheless, the thesis successfully pinpoints areas of improvement in the regulatory framework, providing a strong foundation for future work to address these gaps and facilitate the development of UHS projects.

5.2.2. Quantitative analysis of the network diagrams

After completing the INDs, a quantitative analysis was conducted to assess the dominance of attributes and calculate network metrics. This analysis provided important confirmation of initial observations, particularly the significant roles played by the competent authority and the project developer in the institutional landscape. These findings highlight the centrality of these actors, reinforcing their influence in shaping the regulatory environment for UHS.

While the quantitative analysis was effective in confirming these key observations, it also revealed the challenges of capturing the full complexity of the institutional environment. The generalization of attributes during the formalization process may have limited the potential for deeper insights. Nevertheless, this analysis offers a solid foundation for understanding the core dynamics at play, even if it may not encompass the entirety of the institutional framework.

It is important to acknowledge that the accuracy of these findings is closely tied to the construction of the INDs. As such, validating these diagrams through cross-checking by multiple researchers would enhance the reliability of the results. Despite this, the quantitative analysis provided valuable confirmation of key actors' roles, and with further refinement and validation, future research could yield even more comprehensive insights into the institutional complexity of UHS.

5.2.3. Analysing the rule typologies

Through thorough research into rule typologies and the careful classification of each statement, the analysis successfully highlighted key patterns in the institutional environment for UHS. The classification of statements shed light on how different rules operate and influence stakeholder behaviour, providing a valuable framework for understanding the regulatory landscape and its key characteristics. However, some statements could fit into multiple categories, introducing an element of subjectivity that may affect the consistency of the analysis. This is an important consideration when interpreting the findings, as different researchers might classify the same statement differently.

Recognizing this risk is critical, yet the analysis still offers meaningful insights into how rules are structured and applied. To enhance the objectivity and reliability of the classification, cross-validation by multiple researchers is recommended. Such collaboration would reduce subjectivity and lead to a more robust understanding of rule typologies.

The nuances of rule typology analysis, especially in relation to policy and regulatory frameworks, underscore the potential of this approach to reveal complexities within the institutional environment. While individual expertise was essential in this initial analysis, future research could benefit from collaborative methods, which would provide more comprehensive insights into the functioning of rules across various contexts. By validating and refining the classification process, future studies will strengthen the robustness of these findings, further improving the credibility and applicability of the results.

5.3. Reflection on the research methodology

5.3.1. Identifying relevant policy documents

Identifying relevant policy documents was a crucial step in this thesis, which deviated from the INA method by not including informal data from expert interviews. Instead, the focus on formal institutional statements provided a clear and structured approach to analysing the institutional environment for UHS. This allowed for a systematic examination of policy documents, ensuring that the research remained grounded in formal, codified regulations and frameworks. The comprehensive search was accomplished through a combination of a structured search string and desk research, which ensured a focused and relevant dataset.

One of the strengths of this approach was its ability to precisely map formal institutional structures and highlight key regulatory patterns. By concentrating on formal documents, the research ensured a high level of reliability in terms of traceability. However, a limitation of this approach is the potential exclusion of informal institutional insights, which may offer valuable perspectives on the practical and contextual application of rules. Informal institutions often play a significant role in shaping actions within institutional environments, especially where formal regulations may be ambiguous or incomplete.

Future studies could incorporate expert interviews to enrich the analysis with informal perspectives, thereby providing a more holistic understanding of both formal and informal institutional dynamics. Nevertheless, the structured approach used in this thesis provides a solid foundation for further research, offering valuable insights into the formal regulatory environment for UHS in the Netherlands.

5.3.2. Defining the action arenas

Identifying the relevant action arenas within the research context proved challenging due to the extensive and complex nature of the policy documents, which cover numerous articles and pages. Despite this, the research successfully navigated this complexity by carefully defining action arenas that included key articles without becoming overly broad. This balance was critical to ensuring that the arenas captured essential institutional dynamics while maintaining the readability of the INDs. In doing so, the research was able to highlight core regulatory processes and provide a clear structure for analysing institutional interactions.

One strength of this approach was its ability to clarify and delineate specific areas of institutional focus, making the analysis more manageable and targeted. However, determining the appropriate scope for these arenas was not without difficulties. Overly broad arenas would have resulted in too many institutional statements, which could diminish the clarity and usefulness of the INDs.

Another consideration is that the action arenas in the network diagrams are depicted from a static perspective. While this offers a clear, simplified representation of institutional processes, it does not fully capture the dynamic and simultaneous nature of these arenas. In practice, many of these processes occur concurrently. By representing these arenas as sequential and distinct, the diagrams simplify these interactions, which may obscure the complexity and fluidity of real-world processes.

Despite this limitation, the static representation provides an important foundational view of the institutional structure and key processes. Future research could build upon this by exploring more dynamic representations, which might better capture the simultaneity and interconnectedness of action arenas. Nevertheless, the structured approach taken in this thesis contributes significantly to understanding the regulatory landscape by offering a clear, methodical analysis of institutional arenas.

5.3.3. Formalizing institutions

Policy documents are generally not written as explicit institutional statements, so articles derived from these documents had to be reformulated to fit the ABDICO syntax. The structured approach used in this formalization adds considerable strength to the analysis by ensuring a standardized process, which enhances the traceability of formal institutions back to their original policy documents. This systematic method allows for clear, replicable pathways from institutional statements to their policy sources, increasing transparency and reliability in the research.

Despite this, the formalization was carried out by a single individual, introducing potential bias. The decomposition and reformulation of statements may reflect the researcher's interpretation, which risks altering the original meaning of the articles. Additionally, the translation of Dutch policy documents into English presents challenges, as legal terminology may not have direct equivalents, leading to potential inaccuracies. These factors underscore the need for caution and emphasize the importance of cross-validation and peer review.

To mitigate bias, a large language model (LLM), developed by a fellow thesis student, was used to verify the formalization and coding of articles using the ABDICO syntax. This added another layer of standardization, further improving the traceability and consistency of the data. However, the LLM was not equipped to select relevant articles for analysis, and some important sections may have been missed, particularly in extensive documents like the Environment and Planning Act.

Ideally, multiple researchers would conduct the analysis and compare results to ensure a comprehensive and validated data set. However, time and resource constraints made this step unfeasible in the current research.

5.3.4. Visualizing the network diagrams

The INDs presented in this research were created using PowerPoint, employing a standardized method to ensure consistency and accuracy. Nonetheless, the potential for human error was not fully mitigated.

During the thesis project, efforts were made to develop a prototype INA visualization tool, aimed at improving the precision and efficiency of future analyses. This tool automates the generation of diagrams, thereby reducing the risk of human error in the mapping process. However, the creation of links between institutional statements is still done manually. This manual process introduces the possibility of omitting relevant connections or misclassifying the drivers behind the connections. Such errors can affect the integrity of the network analysis.

To mitigate these issues, further refinement and development of the INA tool are necessary. Despite these limitations, the INA tool represents a significant step forward in systematically analysing and visualizing institutional networks and should be included in future research.

5.3.5. Research verification and validation

First, the results of the INDs were presented and discussed with both Dr. Amineh Ghorbani and Ir. Renske van 't Veer. Although they had been involved in the research from the start, the process of refining the INDs to achieve the final visualization was undertaken by the author. The final outcomes were reviewed, and this verification session was crucial for further refining and revising the INDs based on the feedback received.

Secondly, identifying the correct institutional statements is critical, as these form the database from which the INDs are derived and to which the analysis is applied. Due to the constraints of the research scope and time, it was not feasible to validate these statements through a collaborative method involving multiple researchers coding the same policy documents. Therefore, an alternative approach was adopted. Fortunately, a fellow master's student, Kaninik Baradi, was developing a large language model (LLM) to standardize the process of coding institutional statements. The analysis of policy documents was conducted, and the results were subsequently compared to those generated by the LLM model.

One complexity related to this validation method was the translation of the Dutch policy documents. Since the research context involves Dutch national regulations, all policy documents are originally written in Dutch. Although the author is a native Dutch speaker, this did not pose initial challenges during the analysis. However, the LLM used in the validation was designed to analyse English policy documents. An English version of the Mining Act and Decree was found; however, the newly published Environment and Planning Act and Decree (2024) lacked an English translation.

To address this issue, Kaninik integrated a new module into the LLM to handle Dutch documents. As this module was newly developed and less refined than its English counterpart, the reliability of the outcomes was somewhat compromised. Despite this limitation, the analysis still yielded valuable insights. Overall, the comparative approach proved to be a valid method for ensuring higher accuracy and consistency of the identified institutional statements.

6 Conclusion

To combat climate change, the adoption of renewable energy sources is becoming increasingly critical. However, reliance on these renewables presents challenges, particularly concerning the flexibility and stability of these variable energy sources. To address this, large-scale energy storage projects are being developed to mitigate variability in energy supply. UHS in salt caverns is a key example of such a storage method. Despite extensive research demonstrating the technical feasibility and potential of UHS, the institutional dimension has been largely overlooked. This research study aimed to analyse the institutional network environment governing the development of UHS in salt caverns in the Netherlands.

The proposed approach and research framework offer an effective evaluation of the complex institutional environment surrounding UHS in salt caverns. The study systematically examines a broad range of institutional statements outlined in policy documents, utilizing IG 2.0 syntax and the IAD framework's rule typologies. This research provides both quantitative and qualitative insights into the governance of UHS in salt caverns in the Netherlands, identifying specific institutional voids, conflicts, and hierarchical layers. These findings are crucial for developing insights that inform UHS policy formulations, guide decision-making, and support strategic planning in UHS initiatives.

The goal of this research is to systematically analyse the institutional network and the relations between institutions within this context. To this end, the main research question guiding this study is formulated as follows:

How does the institutional framework impact the development of underground hydrogen storage projects in salt caverns in the Netherlands?

The following chapter addresses each of the sub-questions leading to the answer to the main research question. After which, limitations and recommendations for future research are discussed. Finally, the relevance of this research is highlighted by discussing both its scientific and societal contributions.

6.1. Conclusion of research findings

Sub-question 1

How can the institutional environment of UHS in salt caverns be systematically represented and analysed?

The INA method was selected and applied to analyse the rules governing the development of UHS in salt caverns. This method was chosen for its ability to systematically explore the institutional environment and network. By connecting institutional statements through both inanimate and animate objects, the method captures the chain of actions carried out by actors within a network diagram. Although the original INA method focused on both formal and informal institutions, this research adapted and extended it to better target the analysis of formal institutions in the institutional context.

To achieve this, data collection was exclusively conducted by analysing policy documents to extract formal institutions. Focusing solely on formal rules and regulations allowed for the development of a clear and structured data set that is easier to define, enforce, and evaluate. The data collection was followed by the formalization of institutions using IG 2.0. The methodology was enhanced by introducing a standardized template for coding institutional statements, ensuring transparency and traceability back to their sources.

This research introduced two additional steps to the original INA method. First, a rule typology analysis was conducted to examine the types of rules within the institutional statements, both quantitatively and qualitatively. This analysis provided insights into the key characteristics of the institutional context by revealing the number, composition, and dominant rule types, as well as exploring institutional diversity. Second, the drivers behind the connections between institutional statements were assessed. This focused on understanding the reasoning behind the connections, clarifying the situations in which actors initiate actions and how those actions are classified.

Finally, INDs were created to visualize the formal institutions and their interactions. To better analyse the hierarchy and levels of institutions, an enhancement was made by colour-coding institutional statements derived from Acts and Decrees. This approach provided a clearer overview of the institutional environment's dynamics, offering insights into the robustness and long-term stability of the legislative framework, as well as the processes through which rules are established.

Sub-question 2
How does the institutional environment inform the assessment of project development efforts for UHS in salt caverns?

The second sub-question has been studied through a qualitative and quantitative assessment of the network diagrams and a high-level analysis of the connection between the action arenas.

The qualitative analysis uncovers two key insights related to the second action arena: community and stakeholder engagement. Firstly, there is a misalignment between the policy goals outlined in the Vision and the formal regulations mandated by the Environment and Planning Act. Secondly, the analysis identifies an institutional void regarding the development of a participation process and strategy, as there are no clear guidelines or frameworks governing these processes. These challenges present potential obstacles for project developers, complicating their efforts to align with regulatory requirements and stakeholder expectations.

The quantitative analysis reveals a key insight regarding the dominance of two attributes: the competent authority and the project developer. These attributes are prominently featured in the institutional context, with the competent authority appearing in 22 institutional statements (42%) and the project developer in 21 statements (40%). This distribution underscores their significant roles within the governance of the action arenas. The centrality assessment reinforces this observation, showing that both attributes hold high average centrality scores, with the competent authority scoring 1.7 and the project developer 1.6, highlighting their central influence in shaping institutional outcomes.

Several objects with high embeddedness scores were identified, particularly those related to permit applications and operational plans submitted by project developers. These objects serve as potential bottlenecks for other institutional statements, indicating significant interest from actors due to their influence on related outcomes. The research found that the density of the action arenas ranged between 0.26 and 0.5, suggesting the existence of isolated processes within the overall procedure.

The final assessment of the institutional environment provides a broader analysis of the action arenas depicted in the diagrams. The connections between the diagrams are established to offer a comprehensive understanding of the context and dependencies between outcomes across different arenas. A key insight from this analysis is that the first and third action arenas are interconnected through processes related to the closure plan. While the closure plan is critical for ensuring the safe abandonment of a UHS facility, it must be submitted early during the project's initiation. Consequently, these action arenas do not represent distinct sequential phases but operate in parallel throughout the project development process, continuously influencing one another.

Sub-question 3
What are the key characteristics of the institutional environment surrounding UHS in salt caverns?

The rule typology analysis has revealed that boundary, position, and information rules are consistently present and dominant across the action arenas. This dominance indicates that the institutional framework places significant emphasis on regulating access to and exit from institutional structures, as well as ensuring the effective dissemination of information to relevant third parties. These rules are crucial for maintaining high standards of competence and reliability among the actors operating within the institutional environment.

Additionally, the limited presence of aggregation rules throughout the institutional context is noteworthy. Despite both the Environment and Planning Act and the Vision highlighting the importance of a participatory process, this emphasis is not strongly reflected in the institutional network, suggesting a gap between policy intentions and institutional practice.

Finally, the absence of explicit payoff and scope rules is notable. The lack of payoff rules may be attributed to the nature of the institutional statements, which are derived from formal policy documents. These documents inherently include implicit sanctions due to their obligatory nature, potentially explaining the absence of formalized payoff rules within the institutional framework. Moreover, the lack of scope rules suggests that the roles and responsibilities of actors are not clearly defined or restricted. This aligns with the finding that the competent authority and the project initiator both hold a dominant position in many processes.

Sub-question 4

What analytical insights are derived to understand and potentially enhance the institutional environment for UHS in salt caverns?

First, the research indicates that the current formal institutions do not fully align with the policy intentions outlined by the Dutch government in the Vision. To address the resulting institutional conflicts and voids, it is recommended that large-scale energy storage projects, such as UHS, be integrated not only into the national vision but also into local energy policies and environmental plans. Empowering local government officials to engage with these policies will enable them to better incorporate the needs and perspectives of local communities and stakeholders, leading to more reflective and inclusive policy development.

Secondly, it is advisable for the Dutch government to provide additional guidance in the form of guidelines, templates, and consultations regarding participation strategies for the involved actors. These tools would assist stakeholders in understanding the process and evaluation criteria for participation strategies, thereby mitigating risks associated with the costly and time-consuming development of UHS projects.

Finally, introducing additional scope rules to clearly define the jurisdiction and authority of actors can help reduce distrust and conflicts arising from the dominance of certain attributes. Establishing clear boundaries for each actor's roles and responsibilities will enhance transparency and accountability, fostering a more structured and efficient institutional environment.

Main research question

How does the institutional framework impact the development of underground hydrogen storage projects in salt caverns in the Netherlands?

Despite the technical feasibility and suitability of various salt caverns in the Netherlands for hydrogen storage, there have been limited initiatives from project developers to advance UHS projects. This research offers insights into how the institutional environment influences the slow development of these projects and provides recommendations for policymakers to potentially enhance development efforts.

First of all, the research offers two key insights originating from the second action arena: community and stakeholder engagement. The first insight identifies an institutional conflict between two key policy documents: the Environment and Planning Act and the Subsurface Spatial Planning Vision. This conflict arises from differing objectives of these documents. While the Act mandates third-party participation in planning and decision-making processes, the Vision imposes constraints on this participation. This creates a tension between the broad participatory goals of the Act and the restrictive planning outlined in the Vision.

Additionally, the research identifies an institutional void in the governance of the participatory process. A lack of tangible guidelines on several key aspects of participation. There is no clear framework outlining how third parties should be involved, how their input is reflected in decision-making, or how the success of participation strategies should be evaluated. This gap leaves project developers and other stakeholders without clear direction, creating uncertainty about the effectiveness and legitimacy of stakeholder engagement efforts.

Moreover, the study highlights the central role of the competent authority and the project initiator. Due to their centrality and dominance in the network, these actors have significant influence over the outcomes of the action arenas. Furthermore, the high embeddedness and density measures of various permits and plans underscore their importance, as these objects may act as bottlenecks that could significantly delay processes within the action arenas.

Finally, the research reveals that the institutional environment is predominantly composed of boundary, information, and position rules. This finding suggests that the institutions governing the development of UHS in salt caverns primarily focus on regulating the entry and exit of actors within the context and ensuring transparency through effective information dissemination to relevant stakeholders. This emphasis highlights the priority placed on defining participant eligibility and information sharing, which characterizes the governance and oversight of UHS projects.

6.2. Limitations and recommendations for future research

This research provides a holistic and extensive overview of the rules and regulations governing UHS in salt caverns in the Netherlands. However, several aspects warrant further exploration to deepen the analysis.

Firstly, an important limitation is that the findings have not yet been validated by industry experts, which is a crucial next step to validate the results. This will serve two key purposes: confirming the accuracy and relevance of the findings, and prioritizing the critical issues that need addressing. By doing so, the implementation of solutions can be streamlined, enhancing outcomes for the industry.

Secondly, third-party participation has been highlighted as a critical aspect of the institutional context. However, the findings are based solely on the analysis of formal institutions. As such, another limitation is the lack of validation by third-party stakeholders, including local communities, governments, and organizations. It is therefore valuable to uncover the expected levels of participation from these stakeholders in UHS projects to help define the minimal requirements for effective participation strategies.

Additionally, a limitation of this analysis is its static representation of the institutional environment. The processes described in the action arenas are iterative and overlapping, rather than static. This static representation fails to capture the potential for learning and reflection within the institutional context, particularly as UHS projects are relatively new. Future research could explore these dynamics through modelling tools like Agent-Based Modelling (ABM), which is well-suited for analysing the interactions between stakeholder behaviour and policy changes over time.

Furthermore, this research study focuses exclusively on the Netherlands. However, hydrogen storage in salt caverns is already being used safely in other countries, such as the United States and the United Kingdom. A comparative analysis of the institutional environments in these countries, where UHS is already implemented, could provide valuable insights into the strengths and weaknesses of their policies. Understanding which aspects of international regulations contribute to the successful development of UHS projects, as well as identifying the complexities and challenges they address, could inform improvements to the Dutch legislative framework.

Finally, the research focuses solely on the formal institutions regulating UHS in salt caverns. However, a more comprehensive overview of the institutional environment would also consider informal institutions. Assessing both formal and informal rules may provide further insights into conflicts, as informal practices can vary widely and evolve over time, playing a critical role in shaping stakeholder behaviour. Therefore, future research should include informal institutions to offer a more complete picture of the regulatory landscape.

6.3. Research relevance

6.3.1. Scientific contribution

While the technical feasibility and potential of hydrogen storage in salt caverns have been extensively studied, the institutional dimension is equally critical for the scale-up and roll-out of large infrastructure networks and UHS projects. This research contributes to the academic literature by analysing the institutional rules and regulations that govern UHS development in the Netherlands, offering new insights into the underlying drivers of connections within the institutional environment.

To examine the institutional landscape and formal institutions governing UHS projects, the INA method was employed, yielding two key contributions. First, applying the INA method to the specific context of UHS in salt caverns in the Netherlands represents a novel and highly relevant contribution to the scientific literature. Second, this research advances the INA method by introducing new analytical steps, enhancing its clarity and effectiveness for studying formal institutions. These additions and extensions are discussed below.

First, the study extends beyond merely examining relationships between institutions by investigating the functions of the rules governing the institutional network and how rule typologies influence the institutional environment. A new methodological addition was introduced: assessing the rule typology of each institutional statement. This enhancement aligns with the INA methodology by employing the IAD framework and includes both qualitative and quantitative analyses. The rule typology analysis provides a deeper and more comprehensive understanding of the formal institutions that govern behaviour.

Second, the INA method was further enhanced to explore the drivers behind the connections between institutions and to understand the dependencies affecting institutional compliance. This enhancement involves categorizing institutional relations based on their underlying drivers. By identifying the nature of these drivers, the analysis reveals how institutions influence each other and the mechanisms that enforce or facilitate compliance. This nuanced interpretation of the INDs can inform strategies for policymakers to address institutional conflicts and improve cooperation.

Lastly, the improved INA method incorporates a standardized template for formalizing institutions. This template enhances consistency, efficiency, transparency, and traceability. By including the article number and relevant policy documents from which each institutional statement is derived, the template facilitates cross-validation and ensures greater research transparency. This structured approach allows for clearer verification of institutional claims and supports more robust and accountable research outcomes.

6.3.2. Societal contribution

As global warming becomes an increasingly urgent issue, the decarbonization of heavy industries, such as the steel industry, which are major greenhouse gas emitters, has gained critical importance in societal and political debates. To facilitate this transition, green molecules, such as hydrogen, are becoming essential. Among the various solutions to ensure a flexible and stable energy system, UHS in salt caverns stands out as a technically well-researched method. This technology can effectively bridge the gap between the variable supply of renewable energy sources and the constant demand of heavy industries, offering a reliable means to support decarbonization efforts and mitigate the effects of climate change.

Despite the urgent need for UHS facilities to meet climate goals, uncertainties remain regarding how the institutional environment impacts their development. Potential bottlenecks, institutional voids, and conflicts within the institutional network create obstacles, posing challenges for policymakers in effectively supporting UHS projects. This research addresses these uncertainties by providing a critical analysis of the institutional landscape. From a societal perspective, the work is invaluable: it not only identifies key institutional barriers but also offers a framework to enhance policy support for UHS development. In doing so, the research plays a vital role in advancing a flexible and stable future energy system.

By applying and extending the INA method, this study provides a systematic and comprehensive understanding of the institutional context for UHS projects in the Netherlands. It highlights factors that may be impeding progress and lays the groundwork for more efficient development strategies.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

In the preparation of this thesis research, I have utilized the ChatGPT AI tool to assist with grammar, spelling, reference checks, and sentence rephrasing. After using this tool, I have thoroughly reviewed and edited the content as needed and take full responsibility for the final version of this research.

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A

Formalizing institutions

Table A.1: Rule typology analysis

Rule typology	**Action arenas** Project initiation	Community and stake-holder engagement	Closure, safety, and subsidence control	**Totals**
Position	3	3	4	**10**
Boundary	4	5	8	**17**
Choice	4	2	0	**6**
Aggregation	3	4	0	**7**
Information	5	2	6	**13**
Scope	0	0	0	**0**
Payoff	0	0	0	**0**
Totals	**20**	**16**	**18**	**53**

Action arena 1: project initiation															
Document	**Article**	**Action arena**	**Rule typology**	**#**	**Statement Type**	**[A] Attribute**	**Deontic**	**[I] Aim**	**[B] Direct Object**	**Type of Direct**	**[B] Indirect Object**	**Type of Indirect Object**	**Activation Condition**	**Execution constraint**	**Or else**
Mining Act	15	1	Boundary	1.1	formal	Project developer	must	obtain	Extraction permit	inanimate			When extracting substances from the subsuraface		
Mining Act	15	1	Information	1.2	formal	Competent authority	must	notify	Other stakeholders	animate	By publishing in the Staatscourant	inanimate	If an extraction permit application is recieved	Directly after receiving the application	
Mining Act	15	1	Choice	1.3	formal	Other stakeholders	may	apply	For extraction permit	inanimate			If notified by update in Staatscourant	Within 13 weeks of publication in the Staatscourant	
Mining Act	16	1	Aggregation	1.4	formal	Competent authority	must	involve	Provincial executive	animate			When assessing the extraction permit application	Within reasonable term	
Mining Act	16	1	Aggregation	1.5	formal	Provincial executive	must	involve	Municipality	animate			When preparing the advice to the competent authority		
Mining Act	16	1	Aggregation	1.6	formal	Provincial executive	must	involve	Water board	animate			When preparing the advice to the competent authority		
Mining Act	17	1	Position	1.7	formal	Competent authority	must	assess	Extraction permit application	inanimate			If an extraction permit application is recieved	Within 6 months of receiving the application	
Mining Act		1	Choice	1.8	formal	Competent authority	may	issue	Extraction permit	inanimate			If the application meets required critera		
Mining Act	17	1	Information	1.9	formal	Competent authority	must	publish	Staatscourant	inanimate			If the extraction permit application is issued		
Mining Decree	25	1	Boundary	1.10	formal	Project developer	must	provide	Extraction plan	inanimate	To competent authority	animate	If the extraction permit application is issued	Within 12 months of receiving the permit	
Mining Act	25	1	Boundary	1.11	formal	Project developer	must	obtain	Storage permit	inanimate			When storing hydrogen underground in salt caverns		
Mining Act	26b	1	Information	1.12	formal	Competent authority	must	notify	Other stakeholders	animate	By publishing in the Staatscourant	inanimate	If a storage permit application is received	Directly after receiving the application	
Mining Act	26b	1	Choice	1.13	formal	Other stakeholders	may	apply	For storage permit	inanimate			If notified by update in Staatscourant	Within 13 weeks of publication in the Staatscourant	
Mining Act	27	1	Position	1.14	formal	Competent authority	must	assess	Storage permit application	inanimate			If a storage permit application is received	Within 6 months of receiving the application	
Mining Act	27	1	Choice	1.15	formal	Competent authority	may	issue	Storage permit	inanimate			If the assessed storage permit application meets the requirements		
Mining Act	27	1	Information	1.16	formal	Competent authority	must	publish	Staatscourant	inanimate			If the storage permit is issued		
Mining Act	39a	1	Boundary	1.17	formal	Project developer	must	provide	Storage plan	inanimate	To competent authority	animate	If the storage permit is issued	Within 12 months of receiving the permit	
Mining Act	32a	1	Position	1.18	formal	Competent authority	must	re-assess	All granted storage permits	inanimate			When having issued storage permits	Yearly before 1st of April	
Mining Act	32a	1	Information	1.19	formal	Competent authority	must	publish	Results from the assessment	inanimate	In the Staatscourant	inanimate	If the issued permits have been re-assessed		

Figure A.1: Formalized institutions for action arena 1

Action arena 2: community and stakeholder engagement															
Document	**Article**	**Action arena**	**Rule typology**	**#**	**Statement Type**	**[A] Attribute**	**Deontic**	**[I] Aim**	**[B] Direct Object**	**Type of Direct**	**[B] Indirect Object**	**Type of Indirect Object**	**Activation Condition**	**Execution constraint**	**Or else**
Environ. Act	5.47	2	Boundary	2.1	formal	Project developer	must	apply	For exploration permit	inanimate			If wanting to explore subsurface area for UHS project		
Environ. Act	5.47	2	Information	2.2	formal	Competent authority	must	notify	Community and stakeholders	animate			If there is an application for an exploration permit		
Environ. Act	5.47	2	Position	2.3	formal	Competent authority	must	enable	Community and stakeholders	animate	To provide alternative solutions to problem as defined by the project developer	inanimate	If there is an application for an exploration permit		
Environ. Act	5.48	2	Choice	2.4	formal	Community and stakeholders	may	request	Competent authority	animate	To include independent expert in decision-making process	inanimate	If enabled to propose alternative solution		
Environ. Act	16.39	2	Aggregation	2.5	formal	Commission	must	advise	Competent authority	animate			If environmental permit application		
Environ. Act	16.43	2	Position	2.6	formal	Competent authority	must	assess	Whether the project leads to significant environmentally harmful effects	inanimate			If environmental permit application		
Environ. Act	16.49	2	Boundary	2.7	formal	Project developer	must	provide	MER report	inanimate	To competent authority	animate	If the assessment indicates the project leads to significant enviromental effects		
Environ. Decree	4.2	2	Aggregation	2.8	formal	Municipality	must	advise	Competent authority	animate	On judgement regarding the environmental permit application	inanimate	If the assessment indicates the project leads to significant enviromental effects		
Environ. Decree	4.24	2	Aggregation	2.9	formal	Water board	must	advise	Competent authority	animate	On judgement regarding the environmental permit application	inanimate	If the assessment indicates the project leads to significant enviromental effects		
Environ. Decree	4.25	2	Aggregation	2.10	formal	Provincial executive	must	advise	Competent authority	animate	On judgement regarding the environmental permit application	inanimate	If the assessment indicates the project leads to significant enviromental effects		
Environ. Decree	4.25	2	Position	2.11	formal	Competent authority	must	assess	Exploration permit application	inanimate			If a project developer applies for an exploration permit		
Environ. Decree	4.25	2	Choice	2.12	formal	Competent authority	must	issue	Exploration permit	inanimate			If the assessed application meets the required criteria		
Environ. Decree	5.2	2	Information	2.13	formal	Project developer	must	provide	Notice of intention for exploration	inanimate	To community and stakeholders	animate	If the exploration permit is issued		
Environ. Decree	5.3	2	Boundary	2.14	formal	Project developer	must	include	Who, when, how stakeholders are involved in the notice of intention	inanimate			When providing a notice of intention for exploration		
Environ. Decree	10.2	2	Boundary	2.15	formal	Project developer	must	provide	Participation plan in permit application	inanimate			If environmental permit application		
Environ. Decree	10.2	2	Boundary	2.16	formal	Project developer	must	include	How citizens, companies, social organizations and administrative bodies are involved in the project preparations in participation plan	animate			When providing a participation plan		

Figure A.2: Formalized institutions for action arena 2

Action arena 3: closure, safety, and subsidence control															
Document	**Article**	**Action arena**	**Rule typology**	**#**	**Statement Type**	**[A] Attribute**	**Deontic**	**[I] Aim**	**[B] Direct Object**	**Type of Direct**	**[B] Indirect Object**	**Type of Indirect Object**	**Activation Condition**	**Execution constraint**	**Or else**
Mining Act	44	3	Information	3.1	formal	Project developer	must	notify	Competent authority	animate			If the UHS facility is out of operation	Within 4 weeks	
Mining Act	44	3	Boundary	3.2	formal	Project developer	must	provide	Closure plan	animate	To competent authority	inanimate	If the UHS facility is out of operation	Within 12 months	
Mining Act	44a	3	Position	3.3	formal	Competent authority	must	assess	Closure plan	inanimate			When receiving a closure plan	Within 13 weeks of receiving the closure plan	
Mining Act	44c	3	Boundary	3.4	formal	Project developer	must	remove	Mining installation	inanimate	According to closure plan	inanimate	If the project has come to an end		
Mining Act	44c	3	Boundary	3.5	formal	Project developer	must	provide	Closing report	inanimate	To competent authority	animate	If the UHS mining installation is removed		
Mining Act	44c	3	Position	3.6	formal	Competent authority	must	assess	Closing report	inanimate			If provided by project developer		
Mining Decree	40c	3	Boundary	3.7	formal	Project developer	must	include	Seismic Risk Analysis (SRA)	inanimate	In the closure plan	inanimate	When preparing a closure plan		
Mining Decree	40c	3	Information	3.8	formal	Competent authority	must	notify	Other stakeholders	inanimate	By publishing in the Staatscourant	inanimate	If the closure plan is approved		
Mining Act	41	3	Boundary	3.9	formal	Project developer	must	execute	Measurement plan	inanimate			If the assessed measurement plan is accepted	Before, during and until 30 years after closure	
Mining Decree	30	3	Boundary	3.10	formal	Project developer	must	provide	Measurement plan	inanimate	To competent authority	animate	When developing an UHS project		
Mining Decree	30	3	Position	3.11	formal	Competent authority	must	assess	Measurement plan	inanimate			If project developer provides a measurement plan	Within 8 weeks of receiving it	
Mining Decree	30	3	Boundary	3.12	formal	Project developer	must	update	Measurement plan	inanimate		animate	If the assessed measurement plan is accepted	Every year for the first 5 years	
Mining Decree	31	3	Information	3.13	formal	Project developer	must	provide	Measurement plan results	inanimate	To SodM	animate	If the assessed measurement plan is accepted	Within 12 weeks of the measurements	
Mining Decree	85	3	Boundary	3.14	formal	Project developer	must	have	Disaster response plan	inanimate	For each mining installation	inanimate	When developing an UHS project	Must be updated every 5 years	
Mining Decree	85	3	Information	3.15	formal	Project developer	must	provide	Disaster response plan	inanimate	To the SodM	animate	When finalizing the disaster response plan		
Mining Decree	87	3	Information	3.16	formal	Project developer	must	notify	SodM	animate			If a disaster occurs	When they have the opportunity to	
Environ. Decree	11.5	3	Position	3.17	formal	Competent authority	must	monitor	Potential environmental hazardous activities	inanimate			When classifying a project as potentially environmentally hazardous		
Environ. Decree	11.5	3	Information	3.18	formal	Competent authority	must	publish	Results from monitoring potential environmentally hazardous activities	inanimate			When monitoring potentially environmentally hazardous projects		

Figure A.3: Formalized institutions for action arena 3

B

Institutional Network Diagrams

Table B.1: Connecting institutional statements in the IND, adapted from (Ghorbani et al., 2024)

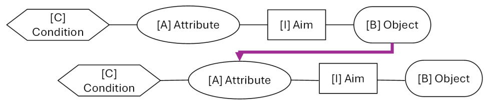
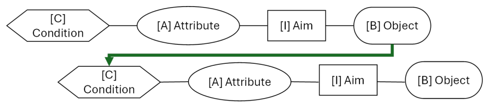
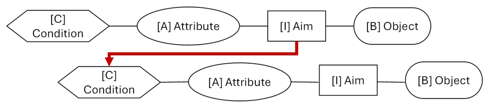
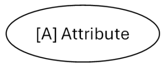
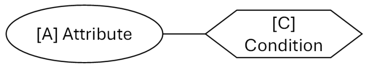
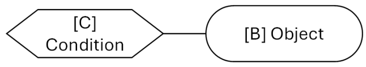
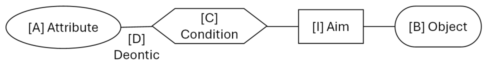
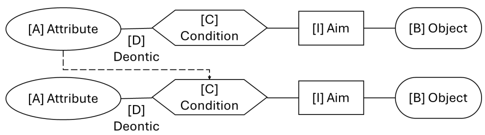
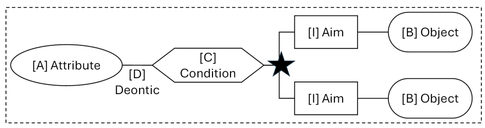
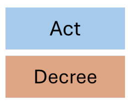
Connecting institutional statements	**Explanation**	**Visualization in IND**
Actor-driven connection	**IF** the [A] Attribute **AND** the [I] Aim, **OR** [A] Attribute **AND** [B] Object are **IN** the [C] Activation condition, **THEN CONNECT** the [B] Object **TO** the [A] Attribute, **OR** the [C] Execution constraint to the [A] Attribute	
Outcome-driven connection	**IF** the [B] inanimate object **AND** [I] Aim are **IN** the [C] Activation condition **OR** [C] execution constraint **AND** [I] Aim **IN** [C] Activation condition **THEN CONNECT** the [B] Inanimate object **TO** the [C] Activation condition	
Sanction-driven connection	**IF THE OPPOSITE** of the [I] Aim is **IN** the [C] Activation condition **OR** [D] Deontic **TEN CONNECT** the [I] Aim **TO** the [C] Activation condition	
Shared activation conditions between institutional statements	If the statements are connected to the same condition node. This simplifies the IND. However, these links should be counted per statement for calculating the network metrics.	-

Table B.2: Step-by-step overview of the Institutional Network Analysis approach, adapted from Mesdaghi et al. (2022)

Step-by-step INA approach	IAD framework	IG 2.0 syntax	Visualization in IND
Defining the **action arenas**	The action arena terminology		Title of the IND
Determine **which** (cluster of) **institutional statements defines** the action arena	Biophysical conditions, attributes of community, rules-in-use		
Define the **primary [A] Attribute** to whom the institutional statement applies	Actor	[A] Attribute	
Create a link between the [A] Attribute and the [C] Condition	Pattern of interaction	[A] Attribute [C] Condition	
Create a link between the **[C] Condition and the [B] Object** of the statement.	Pattern of interaction Level of institutional statements	[A] Attribute [C] Condition [B] Object	
First, state the **[D] Deontic** between the [A] Attribute and the [C] Condition. Second, state the **[I] Aim** of the statement between the [C] Condition and [B] Object	Rules Outcomes	[D] Deontic [I] Aim	
A **formal sanction** is visualized by creating a dashed line from the [A] Attribute to the [D] Deontic. The line is connected to the [C] Condition that states the sanction in case the [I] Aim is not conducted	Rules-in-use	[O] Or else	
An **institutional conflict** may be identified in two ways. First, if two or more institutional statements result in different outcomes within the action situation (indicated with a black star). Second, if the outcome of a formal statement derived from a policy document differs from a goal stated in a non legally-binding document (indicated with a black dashed box).			
The institutional statements are derived from policy documents. These documents are either Acts or Decrees. To be able to analyse the different levels of institutions, the hierarchy in these institutional statements is indicated in two colours. Acts are shown in blue, where Decrees are shown in orange.			
For enhanced clarity and transparency, label each of the institutional statements with the corresponding number for A. the action arena, and B. the rule number according to the formalized institutional statements in Appendix A.			

C
Network metrics

Table C.1: Network metrics used in the Institutional analysis (Daub, 2009; Easley & Kleinberg, 2010; Haythornthwaite & St, 1996; Mesdaghi et al., 2022)

Metric	Description	Range	Degree
Centrality	Measured by the number of links an attribute has, as a ratio of the average number of links attributes have in the network.	[0, ∞]	High degree indicates a key role in the implementation of institutions.
Embeddedness	The ratio of outling links from an attribute to the total number of links in the network. Refers to the fact that behaviour of actors is influenced by their relationships.	[0, 1]	High degree implies a high number of institutions that are dependent on each other for their execution.
Density	Ratio between outdegree links from all objectives, divided by all possible outdegree links. In other words, where all institutions are connected to all other institutions (only possible through conditions).	[0, 1]	A high degree indicates that many institutions in the network depend on the execution of other institutions to carry out tier functions.

C.1. Centrality of attributes

In Table C.2 the centrality metrics for each of the attributes in the action arenas is given.

Table C.2: Centrality measures for each action arena

Action arena	Links per attribute	Total # statements in arena	Total # statements	Centrality
Action arena 1				
Competent authority	11	19	4	2.3
Project developer	4	19	4	0.8
Other stakeholders	2	19	4	0.4
Provincial executive	2	19	4	0.4
Action arena 2				
Competent authority	5	16	7	2.2
Project developer	6	16	7	2.6
Community and stakeholders	1	16	7	0.4
Commission	1	16	7	0.4
Municipality	1	16	7	0.4
Water board	1	16	7	0.4
Provincial executive	1	16	7	0.4
Action arena 3				
Competent authority	6	18	2	0.7
Project developer	12	18	2	1.3

C.2. Embeddedness of objects

In Table C.3 the embeddedness of objects is given.

Table C.3: Embeddedness measures for each action arena

Action arena	Outgoing links	Total links	Embeddedness
Action arena 1			
Extraction permit	3	3	1
Other stakeholders	4	6	2/3
Extraction permit application	3	4	3/4
Provincial executive	2	3	2/3
Municipality	0	1	0
Water board	0	1	0
Staatscourant	0	2	0
Extraction plan	1	1	1
Storage permit	2	2	1
Storage permit application	1	1	1
Storage plan	1	1	1
Issued storage permits	2	3	2/3
Results from assessment	1	1	1
Action arena 2			
How stakeholders are involved in participation plan	0	1	0
How stakeholders are involved in notice of intention for exploration	0	1	0
Participation plan	1	1	1
Notice of intention for exploration	1	3	1/3
To competent authority	1	1	1
Exploration permit	3	3	3/4
To community and stakeholders	2	3	2/3
Action arena 3			
Competent authority	1	1	1
Closure plan	2	3	2/3
Seismic Risk Analysis	1	1	1
Other stakeholders	1	1	1
Closing report	1	1	1
UHS mining installation	2	3	2/3
Measurement plan	5	9	5/9
Measurement plan results	1	1	1
Disaster response plan	3	5	3/5
SodM	1	1	1
Environmentally hazardous activities	1	1	1
Results from monitoring	0	1	0

C.3. Density of objects

In Table C.4 the density of objects is given.

Table C.4: Density of institutional interdependency for each action arena

Action arena	Outgoing links from objects	Density (institutional interdependency rate)
Action arena 1		
Total number of outgoing links from objects	5	0.26
Total number of conditions in diagram	19	
Action arena 2		
Total number of outgoing links from objects	7	0.44
Total number of conditions in diagram	16	
Action arena 3		
Total number of outgoing links from objects	8	0.44
Total number of conditions in diagram	18	