Vulnerabilities Across Technical and Organizational Levels in Hydrogen Transport Infrastructure

A Case Study of Danish Hydrogen Backbone 1: Understanding Vulnerability Mechanisms in the Context of Socio-Technical Integration and Uncertainty

by

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Abstract

The development of hydrogen transport infrastructure is becoming increasingly important for the energy transition, yet this infrastructure is often planned and developed before future producers, market arrangements, and operating conditions are completely established. Under this uncertainty, vulnerabilities may arise not only from the performance of individual assets or the actions of organizational actors in isolation, but also from the interaction points among these, where hydrogen flow, pressure, quality, control information, responsibilities, market arrangements, and operational decisions are coordinated.

This thesis examines how vulnerabilities emerge within and across the technical and organizational interfaces in hydrogen transport infrastructure under uncertainty. The Danish Hydrogen Backbone 1 (DHB1) was used as a qualitative single-case study, combining document analysis with semi-structured expert interviews.

Ten technical and five organizational interfaces were identified and analyzed using an extended version of the Interface Analysis Template, which documented the interacting entities, functions, requirements, types of interdependency, risks, uncertainty, and vulnerability within these interfaces. These were grouped into clusters to explain the vulnerability mechanisms that arise from their interactions, resulting in four clusters covering market access and system balancing, cross-border hydrogen export, the alignment of electricity supply and hydrogen production with network entry, and operational information and control.

The findings indicate that organizational arrangements can limit the availability and use of physical infrastructure, while technical constraints can require operational, commercial, and regulatory responses. Mitigation measures were proposed, including coordinating producer entry and connection processes, creating transparent market access and balancing arrangements, formalizing Danish-German coordination, defining operational responsibilities, and jointly testing organizational and technical arrangements before commercial operation. Together, the Extended Interface Analysis Template and cluster analysis provide a methodological approach for identifying cross-level vulnerabilities and developing early mitigation strategies in emerging hydrogen transport systems.

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1

Introduction

1.1. Background and Context

Hydrogen has become a focal point in European energy-transition strategies, particularly for industrial processes and applications where direct electrification is challenging. However, this increased attention does not indicate the existence of a substantial renewable-hydrogen market. The European Commission reports that hydrogen use in Europe has traditionally been concentrated in chemical production and has primarily relied on natural gas. Current European policy aims to expand renewable hydrogen production and use, while simultaneously developing the infrastructure and market arrangements needed to connect future suppliers and consumers (European Commission, n.d.). This transition requires not only the replacement of production technologies, but also the creation of an integrated system for producing, transporting, trading, and utilizing hydrogen.

Transport infrastructure is an important part of that system. Hydrogen production may develop in locations with favorable renewable-electricity resources, while demand may arise in distinct industrial regions or across national borders. Pipelines, storage facilities, connection points, and measurement and control systems can interconnect these locations, but their development requires coordination with electricity supply, hydrogen production projects, end users, and market regulations. Consequently, European energy-system research emphasizes the need to plan hydrogen production, networks, storage, and cross-border connections, rather than treating them as isolated investments (Kountouris et al., 2024). As a result, hydrogen transport presents both an infrastructure-integration and an engineering challenge.

The scale and timing of the hydrogen transition remain uncertain. According to the International Energy Agency (IEA), low-emissions hydrogen accounts for less than 1% of global hydrogen production, and the number of project announcements significantly exceeds those that have reached final investment decision. The IEA identifies high costs, uncertain demand and regulatory conditions, and slow infrastructure development among the barriers to deployment (International Energy Agency, 2025). For proposed hydrogen networks, uncertainty extends beyond the feasibility of constructing pipelines and stations to include the

alignment of production, demand, operational procedures, and commercial commitments.

Danish Hydrogen Backbone 1 (DHB1) serves as a case study for examining these challenges. DHB1 represents the initial planned configuration of a broader Danish hydrogen transmission network, primarily designed to transport hydrogen produced in Denmark to Germany. The planned system integrates new and repurposed pipeline sections, stations, producer connections, measurement and control functions, and a cross-border export connection. Its successful operation depends on the development of producer projects, electricity grid access, capacity commitments, market procedures, and coordination with the German network (Energinet, 2024d, 2025c, 2026a). As these technical and organizational arrangements are developing together, DHB1 provides an opportunity to identify potential vulnerabilities prior to commercial operation.

1.2. Problem Statement

Hydrogen transport infrastructure is typically characterized by physical assets such as pipelines, stations, valves, metering equipment, and connection points. However, these assets are embedded within a broader socio-technical system, where organizations, contractual relationships, market rules, regulatory decisions, and operating procedures collectively determine whether the infrastructure can fulfill its intended function (Geels, 2004; Gordon, Balta-Ozkan, & Nabavi, 2023). For example, a pipeline may be technically operational, yet hydrogen entry could be restricted by factors such as incomplete producer connections, incompatible delivery conditions, unavailable capacity rights, or insufficient downstream receiving capability.

The main challenge is that a hydrogen transport system's functionality depends on conditions both within and across its technical and organizational levels. For DHB1, technical conditions include pressure, flow, hydrogen quality, monitoring, and isolation, while organizational conditions encompass connection agreements, operating responsibilities, capacity arrangements, and cross-border coordination (Energinet, 2025c).

These conditions are often interdependent: organizational decisions can influence infrastructure usage, and technical constraints may necessitate operational or commercial responses. Research on critical infrastructure interdependencies demonstrates that analyzing system components in isolation can overlook these relationships (Rinaldi, Peerenboom, & Kelly, 2001). Since DHB1's future users, operating patterns, and some detailed arrangements are not yet fully determined, the practical operation of these relationships remains uncertain (Energinet, 2025c). Consequently, this thesis investigates whether and how these dependencies and uncertainties could create vulnerabilities.

Assessing this question is complex because DHB1 has not entered commercial operation yet. Consequently, its future interfaces cannot be evaluated through observed failure data or operational experience from the fully built system. Instead, this analysis relies on existing project documentation and proposed technical and market frameworks to identify potential interface vulnerabilities. It differentiates between documented requirements and assumptions about future conditions. Additionally, it explores how technical and organizational interfaces

might interact across system levels, using expert interviews to review and improve these cross-level interpretations.

1.3. Research Gap

Existing research offers several perspectives relevant to this problem, yet these perspectives often address different levels of analysis without integration. Technical studies focus on hydrogen-pipeline integrity, material compatibility, and safety, whereas hydrogen supply-chain research addresses commercial, investment, and coordination risks (Azadnia et al., 2023; Smedberg et al., 2025; Westphal et al., 2023). While these perspectives identify important potential challenges, on their own, they do not offer a structured account of how conditions at particular technical and organizational interfaces may combine to create broader vulnerability mechanisms within a developing transport project.

Socio-technical research establishes a foundation for analyzing physical infrastructure, actors, and institutional rules collectively, while studies on critical infrastructure interdependencies demonstrate that conditions in connected systems should not be evaluated in isolation (Geels, 2004; Rinaldi, Peerenboom, & Kelly, 2001). European hydrogen-infrastructure modeling likewise shows the importance of coordinating hydrogen production, transmission networks, storage, and cross-border connections (Kountouris et al., 2024). Building on these system-level perspectives, this thesis investigates the specific technical and organizational interfaces through which hydrogen production connects to DHB1, transport is coordinated, and delivery to the German border is enabled.

The remaining gap addressed by this study exists between these two scales of analysis. Identifying a technical or organizational constraint at a single interface does not, by itself, explain how it may interact with conditions elsewhere in the system. Conversely, characterizing the hydrogen network as an interconnected whole can obscure the specific exchanges, responsibilities, and operating conditions through which these interactions occur. This gap is particularly significant for an infrastructure project still under development, as incomplete information about future users, connection designs, operating procedures, and cross-border arrangements creates uncertainty in the relationships between interfaces. Therefore, a more traceable account is required to connect interface-specific conditions and uncertainties to vulnerabilities across technical and organizational levels.

1.4. Research Objective and Questions

In this thesis, vulnerability refers to the susceptibility of the hydrogen transport system to conditions that limit or prevent it from performing its intended functions.

The main objective is to understand how interactions within and between the technical and organizational levels can create or amplify vulnerabilities in hydrogen transport infrastructure. Using Danish Hydrogen Backbone 1 (DHB1) as a case study, the research aims to explain how interdependencies and uncertainty may shape these vulnerabilities and, as a result, identify

measures that could address the resulting vulnerability mechanisms.

The main research question is:

> ***How do vulnerabilities emerge within and across the technical and organizational levels of hydrogen transport infrastructure under conditions of socio-technical integration and uncertainty, and which mitigation measures can address them?***

Five sub-questions guide the analysis:

1. What are the relevant technical components, organizational actors, and system boundaries of the DHB1 case?
2. Which technical and organizational interfaces are relevant to DHB1, and what functions and interdependencies do they involve?
3. What risks and vulnerabilities can be identified at these interfaces within the technical and organizational levels?
4. How do uncertainty and interactions between technical and organizational interfaces contribute to cross-level vulnerability mechanisms?
5. Which measures could address the identified vulnerabilities and cross-level mechanisms?

The questions follow the analytical sequence of the thesis. The first defines the system under study; the second and third identify and assess interfaces within its technical and organizational levels; the fourth examines interactions across those levels; and the fifth considers possible mitigation.

1.5. Thesis Structure

Chapter 2 reviews the literature informing the study's approach to hydrogen transport infrastructure. It examines hydrogen transport as a socio-technical system, the interdependencies among critical infrastructures, and the technical, commercial, and governance-related sources of vulnerability.

Chapter 3 presents the qualitative DHB1 case study design. It details the use of documentary evidence and expert interviews, defines technical and organizational interfaces, describes the adaptation and qualitative scoring of the Interface Analysis Template (IAT), and sets out how interface assessments are brought together into cross-level clusters.

Chapter 4 establishes the case boundary and the criteria for selecting interfaces. It presents the planned DHB1 technical system decomposition and maps the stakeholder categories and roles relevant to its development and operation.

Chapter 5 identifies and assesses the selected technical and organizational interfaces, including their functions, requirements, interdependencies, risks, uncertainties, and vul-

nerabilities through the documentation of the interfaces in the Extended Interface Analysis Template (IAT).

Chapter 6 groups related interfaces into four clusters to examine possible vulnerability mechanisms by which technical conditions and organizational arrangements may influence each other; these are further explained through illustrative scenarios for the case study.

Chapter 7 discusses the findings in relation to the literature, considers the methodological contribution of the Extended IAT and the practical implications for DHB1, develops mitigation measures for the four cross-level clusters, and also examines the limitations and research quality of the study.

Chapter 8 brings together the answers to the research questions and presents the overall conclusions and recommendations.

2

Literature review

2.1. Hydrogen transport as a socio-technical system

Hydrogen transport infrastructure cannot be considered merely as a technical system of pipes, compressors, storage, and terminals. Instead, hydrogen transport is a socio-technical system that combines technical artifacts, organizational actors, market relations, and institutions tightly. This emerging technology is developing under the conditions of energy transition, where it is essential for the construction of new infrastructures to interact safely with pre-existing gas, electrical, and industrial infrastructure and to be aligned with the regulatory framework. Therefore, this approach to studying the infrastructure becomes highly relevant, given that a purely technical understanding of hydrogen transport infrastructure would be too narrow to capture the broader conditions under which vulnerabilities emerge. In this thesis, these socio-technical dynamics are expected to become visible at the interfaces where technical infrastructure, organizational actors, and rule systems intersect.

A useful starting point is Geels' (2004) notion of socio-technical systems. He argues that technologies must be examined not in isolation, but as elements within broader configurations that include infrastructures, user practices, markets, cultural meanings, governance mechanisms, regulations, and actor networks. According to this perspective, the socio-technical system operates based on the fulfillment of a societal purpose, for example, mobility, communication, and energy generation (Geels, 2004). In the context of hydrogen transport, pipelines are just one component of a broader arrangement comprising transmission system operators, industrial users, ports, regulators, ministries, investors, and local communities. These actors do not simply operate around the infrastructure, but they define how the infrastructure is planned, governed, legitimized, and used.

Furthermore, Geels (2004) distinguishes between three different dimensions: systems, actors, and rules. The first dimension refers to material and technological elements, such as networks, physical assets, capital equipment, and supporting resources. The actors dimension includes companies, public authorities, research institutes, consumers, and other social entities involved in the system. The rules aspect comprises regulative, normative, and cognitive institutions that influence the perception of problems by actors and the feasibility

of actions to solve those problems.

This distinction becomes especially important when discussing hydrogen transport due to the fact that numerous challenges in this are not caused by technical aspects alone, but by the interaction of technical systems, social actors, and evolving frameworks. Indeed, the socio-technical approach is also evident in hydrogen-related research. For instance, Gordon et al. (2023) point out that future hydrogen pathways are shaped not only by technical feasibility, but also by the relation between infrastructure repurposing, policy-making, market development, and societal perception. This is clearly illustrated by the authors' examination of domestic hydrogen routes, which discusses gas pipeline repurposing alongside broader socio-technical issues.

This broader perspective is also supported by current hydrogen literature. The report published by the IEA in its *Global Hydrogen Review 2025* demonstrates that the topic of hydrogen transport has become more connected to an overall build-up of infrastructure, covering production facilities, industrial centers, ports, storage, and cross-border corridors (International Energy Agency, 2025). Such projects are not motivated solely by engineering factors, but also by industrial policy, climate targets, trade ambitions, and energy security concerns. In practice, hydrogen transport projects take place in multi-actor planning processes and are shaped by uncertainty regarding demand, regulation, financing, and future market organization.

This suggests that hydrogen transport must be analyzed as a socio-technical and governance challenge, rather than a technical design problem. In this context, potential vulnerabilities are related not only to the technical performance of assets but also to how responsibilities, knowledge, and decision-making are distributed across organizations and levels of governance.

From a socio-technical perspective, an important question is why existing energy systems tend to remain stable and how earlier choices constrain subsequent development options. According to Geels (2004), socio-technical regimes are more likely to become locked-in through sunk investments in the current infrastructure, accumulated expertise and routines, dense actor networks, and reciprocal reinforcement among different sets of shared rules and institutions. This point is very relevant to the development of hydrogen transport infrastructure, as it is being built together and partially embedded within well-established regimes for natural gas and electricity.

It can be anticipated that pre-existing planning, regulation, and engineering procedures developed within the context of gas pipelines will be reused or modified when designing hydrogen pipelines and associated assets. However, such an approach can reduce the extent to which hydrogen-specific factors are taken into account, thus cementing the decision-making process that becomes harder to change at a later stage (Geels, 2004). Additionally, incumbent organizations may promote the adoption of hydrogen technologies when it aligns with their interest while resisting any shifts that undermine their infrastructure, expertise, and competitive position. In other words, vulnerabilities in hydrogen transport systems arise to some extent as a consequence of long-lasting institutional arrangements, power asymmetries, and coordination between the emerging hydrogen infrastructure and the current systems that it has to interact with (Geels, 2004; International Energy Agency, 2025).

In addition, the literature on socio-technical transitions is relevant to this study since it views hydrogen from a broader perspective of system transformation. According to Geels' multilevel perspective, three types of processes occur within socio-technical transitions – namely, niches, regimes, and landscape (Geels, 2004). In this way, hydrogen transport may be viewed as an example of a transition from niche to regime, which means that hydrogen-related projects are emerging and are usually shielded by policy interventions but are also subjected to broader pressures from the landscape, such as decarbonization goals, political uncertainty, and changes in European energy policy. These landscape pressures and regime dynamics shape not only whether hydrogen infrastructure develops, but also when key components of the infrastructure are built and how organizations share roles and responsibilities at the points where their infrastructure connects. The relevance of this aspect to the current research lies in the assumption that vulnerabilities would emerge at points of intersection of emergent hydrogen networks and established infrastructures and rule systems.

2.2. Interdependencies and vulnerability in infrastructure systems

One important theme discussed in the literature related to critical infrastructures concerns the idea that essential systems must be considered not as individual networks but rather as elements of a larger constellation of interdependent systems. This becomes relevant, especially when considering hydrogen transportation, which most likely would not exist as an isolated network but rather as one infrastructure embedded within a larger set that involves elements such as the electrical grid, natural gas, computerized control systems, port facilities, and industrial users. Therefore, the literature on critical infrastructure interdependencies, cascading effects, and high-risk technologies provides an important theoretical framework for understanding how vulnerability can propagate through the hydrogen transport infrastructure and concentrate at specific technical, organizational, and cross-level interfaces.

2.2.1. Critical Infrastructure Interdependencies

One widely cited paper in this area is that of Rinaldi, Peerenboom, and Kelly (2001), who argue that infrastructures such as electrical systems, telecommunications, transportation, water supply, and fuel systems should be approached as a "system of systems," given that the condition of one of these infrastructures has a great influence on others. Their differentiation between dependencies, where one infrastructure relies on another, and interdependencies, where infrastructures mutually depend on each other, is helpful because it clarifies whether a relationship is one-directional or mutual, which is important when identifying how failures propagate through interfaces (Rinaldi, Peerenboom, & Kelly, 2001). Some examples of cascading effects, such as the Galaxy 4 Satellite event and the California power crisis, illustrate how interconnections within infrastructure may lead to failures that propagate across a wide range of infrastructures over a wide geographical region (Rinaldi, Peerenboom, & Kelly, 2001).

Rinaldi et al. (2001) list four categories of interdependencies. Physical interdependencies refer to interrelated systems that rely on the material outputs of other systems, such as electricity required for pump operation and fuels for power plants. Cyber interdependencies

concern reliance on information flows via communication networks, like SCADA and energy management systems. Examples of geographic interdependencies include situations in which several infrastructure systems coexist geographically and are thus exposed to the same risks provoked by local events, such as flooding or earthquakes. Finally, logical interdependencies refer to non-physical relationships shaped by policies, market arrangements, or institutional decisions (Rinaldi, Peerenboom, & Kelly, 2001).

Furthermore, infrastructure is conceptualized as a complex adaptive system comprising multiple agents whose behavior and interactions result in emergent properties of the system as a whole (Rinaldi, Peerenboom, & Kelly, 2001). This typology and the systems perspective offer an organized foundation for subsequent analysis of the relationship between hydrogen transport infrastructure and electrical power, gas, ports, CO_2, and digital infrastructures. For hydrogen transport, this means that understanding vulnerabilities requires tracing how these four types of interdependency converge at concrete interfaces, where physical assets (such as pipelines, compressor stations, and grid connections), organizational arrangements between actors, and regulatory or market rules come together.

Rinaldi et al.'s framework is especially useful because it is broad and very practical. It does not stop at technical links between systems but also covers non-material dependencies, such as institutional and regulatory relations, which are very important for hydrogen transport. On the other hand, the model lacks theoretical depth. As such, it works well at recognizing and classifying interdependencies, but is less developed in explaining why some interdependencies become more destabilizing than others, or how they evolve over time within broader socio-technical transitions. Thus, for this thesis, it serves as an analytical tool that requires supplementation from other literature addressing dynamics and systemic fragility more directly.

2.2.2. Cascading failures in interdependent networks

From a network science perspective, systemic fragility in interdependent settings can be defined more formally. According to Buldyrev et al.(2010), removing just a few nodes from one network can trigger an iterative failure process that affects the entire interdependent network, due to dependencies between nodes across different infrastructures. In other words, interdependent infrastructures may prove much more fragile than their isolated counterparts, meaning that a structure that appears robust in a single-network context may turn out fragile when considering dependencies between infrastructures.

For example, Buldyrev et al. (2010) demonstrate that tightly interdependent infrastructures may suffer from repeated knock-on effects as a result of even a small initial failure, causing both networks to collapse suddenly rather than gradually. This pattern was evident in the case of coupled power and communication networks during the 2003 Italian blackout, when apparently inconsequential events had catastrophic effects because the infrastructure was highly dependent on the other.

While this thesis will focus on theoretical implications rather than practical applications of Buldyrev et al.'s approach, it can still offer valuable insights. The assumptions concerning the topology of interdependent networks and the dependencies themselves made in this model

cannot be readily applied to hydrogen transportation. Nevertheless, this work provides important theoretical input regarding the cascade potential: even small local disruptions may have severe system-wide effects once the socio-technological system becomes fragile due to tight interdependencies among the infrastructures on which its components rely.

2.2.3. High-risk technologies and "normal accidents."

The second stream of literature looks at the features characterizing high-risk technologies. Perrow's Normal Accidents theory claims that certain systems may be fundamentally prone to accidents because they possess both interactive complexity and tight coupling (Perrow, 1984). As explained by Perrow, interactive complexity refers to the possibility of unexpected interactions between components, whereas tight coupling denotes a lack of slack, rigidity of operations, and no possibility to improvise in case of failures. Systems that possess both characteristics at the same time make accidents inevitable, in the author's opinion, because small, apparently unconnected failures will interact in unexpected ways and make safety mechanisms useless. Therefore, accidents are systemic in such cases.

Considering hydrogen transportation in particular, it is apparent that not only interdependencies but also tight coupling and interactive complexity may affect risk. Indeed, a number of interfaces in a future hydrogen backbone will most likely feature tight coupling and interactive complexity due to high coupling between hydrogen pipelines, power systems and ICT used to manage them. Operational requirements such as maintaining pressure and quality, matching fluctuating injections and offtake, and coordinating with electricity system constraints may further reduce slack at these interfaces. Yet the Normal Accidents Theory does not provide any additional guidance on how to differentiate between different kinds of interdependencies and analyze governance arrangements. It offers a lens to characterize the overall riskiness of system configurations, but does not specify how responsibilities, decision rights, and information flows should be organized to mitigate those risks.

2.3. Integrity and commercial risks in hydrogen transport systems

2.3.1. Technical integrity and safety of hydrogen pipelines

Recent literature shows the specific integrity and safety concerns associated with the transportation of hydrogen via pipelines, especially when repurposing components of the existing natural gas network. Smedberg et al. (2025) show that hydrogen in its gaseous form can alter the mechanical behavior of steel pipes, reducing their ductility, fracture toughness, and fatigue crack growth resistance. Moreover, hydrogen may permeate through polymeric materials used to build distribution networks, which raises concerns about continuous leakage, especially in confined spaces. These suggest that the technical performance of a future hydrogen backbone cannot simply be seen as a scaled version of current natural gas systems, because its performance will depend on how materials and operating conditions interact over time in service.

As far as pipe integrity is concerned, most of the issues and defects that may arise in connection with natural gas transportation are also important when dealing with a hydrogen pipeline. For instance, defects such as cracking, dents, gouging, corrosion, and pipe damage due to ground movements must be considered. The only differences here are increased sensitivity of these defects to hydrogen embrittlement and a higher rate of fatigue crack growth, along with the low fracture toughness of some steels. Furthermore, according to Smedberg et al. (2025), existing knowledge on hydrogen impacts is primarily based on experimental data from small-scale laboratory tests, while there remains a need for full-scale validation of typical pipeline defects under realistic pressure cycles and operating conditions. Similar concerns apply to the problem of hydrogen pipeline inspection, as existing in-line defect assessment standards such as API 579-1 and BS 7910 should be further validated to ensure reliability in detecting degradation related to hydrogen.

On the other hand, for polymeric pipelines, the main concern is not embrittlement but rather permeation. Estimated losses are economically small on a percentage basis, but there is significant concern about surface area, which can be very large in real pipeline networks, and the potential leakage of hydrogen into an enclosed space, which poses hazards and raises regulatory concerns. In addition, the long-term properties of polymers, joints, and welding under hydrogen conditions have not been sufficiently documented in order to make a proper judgment on conversion. Overall, the literature review of technical issues points to a number of integrity and safety uncertainties that concentrate at technical interfaces: welds, joints, transitions between materials, connections between repurposed and new assets, and points where hydrogen pipelines meet other infrastructures or facilities.

2.3.2. Supply chain and commercial risks at organizational interfaces

Beyond engineering risk, an increasing number of studies focus on green hydrogen supply chain risks, including those associated with transportation. Among others, Azadnia et al. (2023) list 43 risk factors for the European green hydrogen supply chain and rank them using a Delphi process and the best-worst method, with a focus on hard-to-abate industries. Among the factors listed as the most important risks are high capital costs for production and transport equipment, low electrolyzer capacity, policy and regulatory development, disruptions or failures in supplying electricity generated from renewable resources, and a lack of storage, transportation, and distribution capacities.

The first two of these are closely connected: electrolyzers are the core technology of green hydrogen production, using electricity to split water into hydrogen and oxygen, so their installed capacity, together with the availability of renewable electricity, governs how much hydrogen can be produced and delivered to transport infrastructure such as pipelines. A low electrolyzer capacity, or delays in scaling it up, therefore limits the utilization of the surrounding infrastructure and the viability of large-scale transport and storage facilities. Consequently, several of these risk factors can be attributed directly to the development of hydrogen transport infrastructure, due to uncertainties regarding pipeline development, the network connection of the electrolyzer, and the viability of large-scale transportation and storage facilities.

Azadnia et al. (2023) also show that technological and infrastructure risks have much in common with governance and market risks. Policy and regulatory risks appear to be important because of existing uncertainty concerning standards for hydrogen technology, support scheme eligibility, and the stability of financial incentives. Consumer acceptance, health and safety, and quality of hydrogen production are also considered risks which necessitate development of certain standards and certification systems, including guarantees of origin and purity standards. While the article considers various modes of transport, including pipelines, road, rail, and maritime transport, hydrogen transport infrastructure appears as a series of logistics stages within a supply chain. Such an approach does not provide sufficient analysis of the particular convergence points of the identified risks, such as contractual and organizational interfaces between stakeholders and physical interfaces between assets and modes of transport.

In their policy brief, H2Global Stiftung provides a similar understanding of commercial interfaces within hydrogen supply chains. Through analysis of green ammonia as a hydrogen derivative, Westphal et al (2023) state that hydrogen and its derivatives are initially transported through many countries, which have different regulations and standards, while moving through long and complicated value chains, including stages of production, conversion, transportation, and storage. According to the authors, commercial risks should be addressed at any handover point, meaning that the risks do not appear to stem from physical assets alone. Rather, transition points are also critical as they represent certain responsibilities, risks, and obligations of actors. The brief identifies three types of problems that can occur at these interfaces: information problems, motivation or incentive problems, and synchronization problems.

The information problem arises because potential trading partners must know each other's needs and capabilities, which is difficult in an emerging market where the market participants and their roles are still taking shape and where uncertainties about future infrastructure and demand remain. The motivation or incentive problem stems from an economic viability gap: producing hydrogen still costs more than consumers are willing to pay, so investments are not yet profitable on their own. In addition, early investments risk losing value as technologies develop and costs fall. The synchronization problem arises because the value of an investment in one stage of the value chain depends on simultaneous investments by other actors, leading each actor to wait for the others before committing. Such problems may hamper the creation of viable supply chains despite the feasibility of the technologies.

2.4. Organizational and governance structures shaping hydrogen interfaces

The framework for the transport of hydrogen is being shaped within an international governance context that is fragmented and continuously changing. According to Lentschig et al. (2025), the global hydrogen economy features many initiatives dealing with multiple issues related to end-use sector development, cross-border infrastructure and trade, as well as environmental and socio-economic perspectives. As a result, there is a polycentric structure in which the different organizations promote partly overlapping standards, regulatory

frameworks, and market designs.

In relation to a hydrogen backbone in the North Sea region, this implies that projects have to take into consideration the regulations set by the EU, the regional cooperation structures as well as the rules established on the global market. Implementation timetables, demand creation and sustainability criteria may vary across these different levels, and some fundamental elements such as guarantees of origin and definitions of low-carbon hydrogen are still subject to change.

For this thesis, these features of multilevel, polycentric governance are viewed as a source of cross-level interfaces between the technical and organizational dimensions of hydrogen transport. At these interfaces, EU policy and targets meet national planning, permitting and investment decisions, which shape how technical design choices, operating regimes and safety measures are specified for concrete pipeline projects. Building on Lentschig et al.'s (2025) observation that hydrogen governance is fragmented across multiple initiatives and levels, this thesis identifies those misalignments across levels as possible drivers of vulnerabilities at technical and organizational interfaces. For example, changing eligibility criteria, evolving standards, or misaligned timelines can lead to redesigns, delays, or infrastructures whose technical configuration no longer fits the institutional environment in which they must operate, making these cross-level interfaces relevant to the analysis of vulnerabilities.

2.5. Synthesis and research focus

The literature review shows that hydrogen transport infrastructure represents a socio-technical system where technical elements, organizational actors, and governance regimes are closely interconnected. Socio-technical and transition studies show that its development is shaped by existing energy regimes, actor coalitions, and institutional path dependencies (Geels, 2004). Research on infrastructure interdependencies shows that disturbances can propagate through physical, digital, and institutional links, often concentrated at points where different infrastructures and control systems meet (Buldyrev et al., 2010; Rinaldi, Peerenboom, & Kelly, 2001). Work on normal accidents, material integrity, and hydrogen supply chains adds that tight coupling, integrity uncertainties, and misaligned commercial arrangements can intensify disturbances, particularly at handover points where responsibilities and information are transferred (Azadnia et al., 2023; Perrow, 1984; Smedberg et al., 2025).

Taken together, these findings support analyzing hydrogen transport systems as part of the wider network of interdependent infrastructure systems. Rinaldi, Peerenboom, and Kelly (2001) offer a typology for classifying these interdependencies, Buldyrev et al. (2010) show how they can escalate minor disruptions into system-wide failures, and Perrow (1984) stresses that tight coupling and complexity make systems challenging to control even when risks are known. Interface vulnerabilities therefore cannot be considered merely local technical issues. They may arise through combinations of material dependence, digital control, spatial location, institutional coupling, and tightly sequenced operation, and their severity depends on how an interface is embedded in wider operational routines, control architectures, and governance arrangements.

Technical studies highlight uncertainties in welding, joining, material changes, and the integration of new and repurposed assets (Smedberg et al., 2025), while supply-chain and governance studies identify misalignments in financial incentives, regulations, and contractual relationships where different actors and implementation phases interact (Azadnia et al., 2023; Lentschig, Patonia, & Quitzow, 2025; Westphal et al., 2023). These risks reinforce one another at points where information, decisions, and responsibilities are transferred.

For the Danish hydrogen backbone, this means that risk assessment should extend beyond individual component safety and broad supply-chain risk categories. It should consider how technical interfaces, such as those between pipelines and storage or between repurposed and new infrastructure, intersect with commercial and regulatory interfaces. For this thesis, these findings indicate that vulnerabilities are likely to arise at technical and organizational interfaces and their interactions, especially under uncertainty. Interfaces are shaped by assumptions about future demand, regulation, and infrastructure that may later prove inaccurate, leading to misalignment between how the system is designed and how it is expected to operate. The thesis therefore identifies and maps how vulnerabilities emerge at these interfaces, the role of uncertainty, and the measures that could mitigate them.

3

Methodology and Analytical Framework

3.1. Research Design and Case Selection

This thesis adopts a qualitative single-case study design to examine how vulnerabilities may emerge within and across the technical and organizational dimensions of hydrogen transport infrastructure under uncertainty. The research is both exploratory and explanatory. It is exploratory because hydrogen transmission infrastructure is still developing and many technical, market, regulatory, and organizational arrangements have not yet been completely established. It is explanatory because the study seeks to understand how dependencies, uncertainty, and interactions between technical and organizational elements may contribute to the formation of vulnerabilities.

The study uses Danish Hydrogen Backbone 1 (DHB1) as the empirical case. DHB1 was selected because it represents an emerging socio-technical infrastructure system where physical hydrogen infrastructure is closely connected to organizational, market, regulatory, and cross-border arrangements. The planned system includes new and repurposed pipeline sections, stations, producer connections, measurement and control systems, and a cross-border connection towards Germany. At the same time, its development depends on actors including the Danish transmission operator, hydrogen producers, shippers, regulators, public authorities, and the German transmission system operator. These characteristics make DHB1 a suitable case to examine vulnerability not only within individual technical components or organizations, but also at the interfaces between and across them.

A second reason for selecting DHB1 is its early stage of development. The system has not yet entered commercial operation, and several conditions affecting its future development and use are still being shaped. These include producer connections, electricity-grid access for PtX (PtX refers to technologies that convert electricity, typically from renewable sources, into other energy carriers or products, such as hydrogen, ammonia, methanol, or synthetic fuels) projects, capacity commitments, balancing arrangements, tariff structures, detailed operating procedures, and coordination with the German hydrogen system. In the context of DHB1, the relevant PtX facilities are electrolysis plants that produce hydrogen using renewable electricity and inject it into the hydrogen transmission network.

The case therefore allows vulnerability to be examined while important technical and organizational arrangements are still being defined rather than only after the infrastructure has entered operation. This is particularly relevant to the research focus on uncertainty and on how assumptions made during planning and development may influence future system vulnerability.

DHB1 also provides a relevant cross-border case because its intended function depends on coordination between the Danish hydrogen transmission system and the connected German infrastructure. The case therefore contains dependencies extending beyond a single asset, organization, or national system. While the analysis is specific to this case, the types of interfaces examined are also relevant to other emerging hydrogen transport systems.

Interfaces are used as the main unit of analysis. Rather than assessing technical assets or organizational actors separately, the study focuses on the points at which components, actors, information, responsibilities, physical flows, and operating conditions interact.

The research process consists of five connected methodological steps, illustrated in Figure 3.1. Each step produces an output that supports the following stage of the analysis. The process begins with the definition of the case and system boundary and the collection of case evidence. The physical system is then decomposed and the relevant stakeholders are mapped. These steps provide the basis for identifying technical and organizational interfaces, which are documented and assessed using the Extended Interface Analysis Template (IAT). Related interfaces are subsequently combined into cross-level clusters to identify pathways through which vulnerability may emerge between technical and organizational levels. The preliminary cluster interpretations are then reviewed and refined through expert interviews as part of Step 5. Lastly, the resulting vulnerability mechanisms subsequently inform the discussion of mitigation measures in Chapter 7.

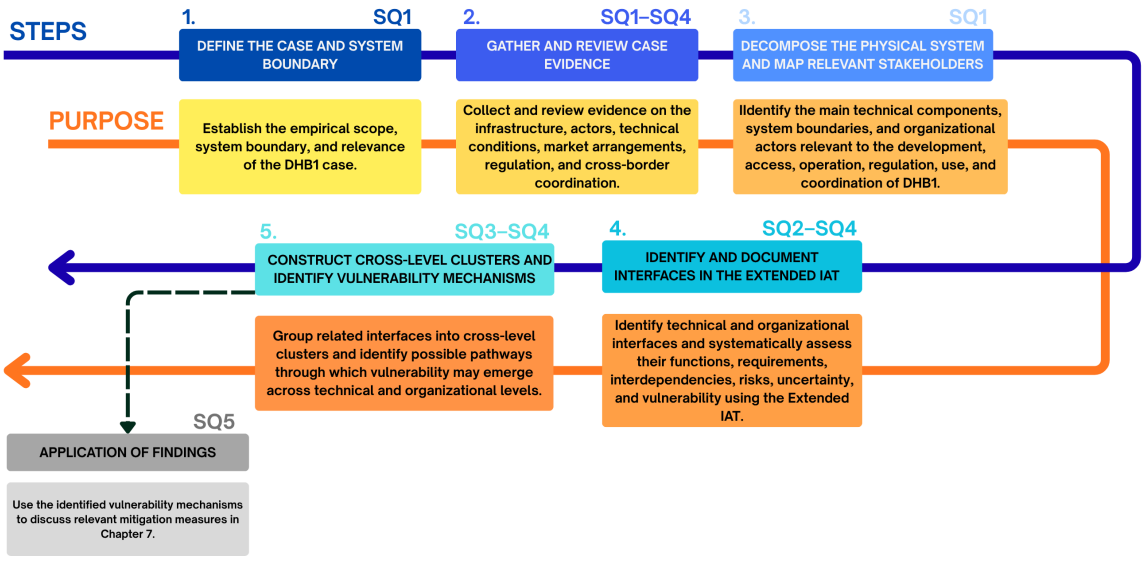

Figure 3.1: High-level methodological workflow and alignment with the sub-research questions. Steps 1–3 are presented in Chapter 4, Step 4 in Chapter 5, and Step 5 in Chapter 6; the resulting vulnerability mechanisms inform the mitigation measures discussed in Chapter 7 (SQ5).

Note. Author's representation of the research process.

3.2. Data Collection

3.2.1. Document Analysis

This thesis used document analysis as the main data-collection method. It constituted the primary method to gather evidence, which relates to Step 2 of the research process, and provided the empirical basis for the subsequent system mapping and interface analysis. The documents were used to identify and describe the technical and organizational context of Danish Hydrogen Backbone 1 (DHB1), as well as the dependencies, risks, and uncertainty conditions associated with the identified interfaces.

This approach was considered appropriate because DHB1 is currently under development. Many of the conditions relevant to the future system, including technical specifications, connection arrangements, balancing procedures, tariff structures, and cross-border coordination, are currently documented in project plans, regulatory material, technical documentation, and proposed arrangements rather than through operational experience.

Documents were included when they provided evidence relevant to at least one of the main analytical needs of the study: (1) the physical configuration and intended operation of DHB1; (2) the roles and responsibilities of relevant actors; (3) technical or operational conditions at system interfaces; (4) market, regulatory, or contractual arrangements; (5) cross-border coordination; or (6) uncertainty affecting the development and future operation of the system. This selection approach ensured that the documents were directly relevant to the system boundary and research questions.

The most relevant sources were Energinet's *Information Package 2: Danish Hydrogen Backbone* and *Information Package 3: Danish Hydrogen Backbone 1* (Energinet, 2024d, 2025c). These documents provided the main case-specific evidence for defining the DHB1 system boundary, developing the technical decomposition, identifying relevant stakeholders and interfaces, and completing the Extended Interface Analysis Template (IAT). They provided information on the planned pipeline configuration, stations, injection and extraction connections, pressure conditions, hydrogen quality, linepack, market access, balancing, user roles, connection arrangements, and interaction with the German hydrogen system.

Further Energinet documents were analyzed to understand the organizational, commercial, and regulatory conditions surrounding DHB1. These included documentation on balancing arrangements, economic regulation, capacity sales, connection processes, electricity-grid access for PtX projects, tariff methodologies, and related regulatory developments. These sources were particularly relevant to the organizational interfaces involving Energinet, shippers, direct producers, PtX developers, and the Danish Utility Regulator, and to the assessment of uncertainty related to market access, capacity allocation, tariffs, balancing, grid connection, and regulatory approval (Energinet, 2024a, 2024c, 2025b, 2025d, 2026b).

For the Danish-German export interface, the analysis included documentation from Energinet and Gasunie Deutschland concerning the development of the cross-border hydrogen corridor, together with publicly available information on Hyperlink 3. These sources were helpful for assessing dependencies related to project timing, cross-border capacity,

infrastructure compatibility, downstream availability, and coordination between the Danish and German transmission systems (Energinet, 2026a; Gasunie Deutschland Transport Services GmbH, 2026).

Technical standards and industry reports were used where additional technical context was required. ASME B31.12, CEN/TS 17977, and guidance from the European Industrial Gases Association were used to support interpretation of technical conditions related to hydrogen-pipeline operation, hydrogen quality, pressure management, isolation, venting, and safety at station and connection interfaces. These sources were not treated as evidence of the specific DHB1 configuration. Instead, they were used to interpret technical requirements, uncertainties, and potential risk mechanisms identified from DHB1-specific documentation (American Society of Mechanical Engineers, 2023; European Committee for Standardization, 2023; European Industrial Gases Association, 2023).

Documents relating to PtX development and electricity-grid access were also reviewed to support the analysis of the upstream electricity-to-hydrogen chain. These sources were used to examine the relationship between electricity-grid access, PtX project development, producer-side infrastructure, and potential hydrogen entry into DHB1. Documentation on limited grid access informed the assessment of electricity-side constraints (Energinet, 2024a). The early connection process and draft pre-construction agreement informed the assessment of project maturation, connection responsibilities, and producer-entry conditions (Energinet, 2025b, 2025d).

The documents were reviewed systematically according to the analytical information required in the later stages of the study. During the initial system mapping, information was extracted on physical components, system boundaries, stakeholder roles, responsibilities, and relationships. These findings were used to develop the technical decomposition and stakeholder mapping presented in Chapter 4. In the following interface-analysis stage, relevant documentary evidence was reviewed for each identified interface to establish the interacting entities, type of exchange, interaction function, requirements, interdependency type, interface-specific risks, and uncertainty conditions. Technical documents primarily informed physical assets, operating conditions, hydrogen-quality requirements, measurement and control functions, and safety conditions, while market, regulatory, and policy documents informed actor responsibilities, capacity arrangements, tariffs, balancing, approval processes, and governance conditions.

The output of the document analysis was not a single dataset, but a structured evidence base that developed progressively through the analytical process. First, it supported the definition of the system boundary, technical decomposition, and stakeholder mapping in Chapter 4. These outputs were then used to identify and assess technical and organizational interfaces through the Extended IAT in Chapter 5. The resulting interface profiles provided the documentary basis for the preliminary cross-level vulnerability clusters developed in Chapter 6.

3.2.2. Expert Interviews

Semi-structured interviews were conducted after completing the document-based analysis and initial cross-level cluster formation. As shown in the methodological overview in Figure 3.1, the expert interviews in Step 5 reviewed and improved the initial cross-level clusters and vulnerability mechanisms derived from the document interface analysis. These interviews were not intended to verify every technical requirement or assessment documented in the Extended Interface Analysis Template (IAT). Instead, their goal was to review and refine the understanding of cross-level vulnerability mechanisms that emerged when technical and organizational interfaces were analyzed together.

The interviews were used to assess whether proposed cluster logic and vulnerability mechanisms were plausible, relevant, and sufficiently complete to represent the developing DHB1 system. Interviewees were asked to identify missing interfaces, actors, dependencies, or uncertainty conditions; challenge proposed relationships between organizational arrangements and technical conditions; provide examples from their professional experience that could support, qualify, or challenge the proposed mechanisms; and suggest possible mitigation measures.

Interview participants were selected purposively based on expertise needed to review the preliminary cross-level analysis. The objective was not to obtain a statistically representative sample or to include a representative from every stakeholder group identified in Chapter 4. Instead, the aim was to obtain complementary perspectives across the main technical, operational, project-development, and regulatory areas represented in the interfaces and clusters.

Selection was informed by the stakeholder mapping, but interviewees were selected according to their expertise rather than as formal representatives of stakeholder categories. In addition, not all stakeholder categories identified in the mapping could be represented by a clearly identifiable organization at the time of the study. This was relevant, in particular, for future hydrogen consumers and off-takers. Although these actors are important to the DHB1 market model, publicly available information did not yet clearly identify which companies would purchase or receive hydrogen transported through the Danish system. The developing nature of the hydrogen market therefore limited the ability to select interviewees from every stakeholder category.

The final sample included four experts with complementary areas of expertise: two Energinet experts specializing in hydrogen-market development and gas-system operation, respectively; a technical-safety lead from Copenhagen Infrastructure Partners involved in large-scale PtX development; and a specialist from the Danish Utility Regulator with expertise in gas and hydrogen-network regulation. The experts are identified as Experts 1-4 throughout the thesis. Their professional backgrounds and contributions to the analysis and mitigation measures are summarized in Appendix D.

Before each interview, participants received a preliminary cluster-analysis document. For each cluster, the document presented the technical and organizational interfaces included, the rationale for grouping them, the proposed cross-level vulnerability mechanism, and illustrative vulnerability scenarios. The preliminary document for the interviews are reproduced in

Appendix E.

The expert review consisted of interviews with the four selected experts. These were conducted online or by telephone and lasted approximately one hour each. Participants were invited to address the questions and clusters relevant to their expertise, commenting on the relevance and completeness of the included interfaces, the plausibility of the proposed relationships and vulnerability mechanisms, and possible mitigation measures. Feedback was documented through interview notes, supplemented by written comments provided by the experts.

Following each interview, the notes and written comments were reviewed and compared with the relevant cluster interpretation and underlying documentary evidence. Proposed changes were considered where feedback identified a missing dependency, clarified a relationship between technical and organizational conditions, challenged an assumption, or provided additional context for an illustrative scenario. After all four interviews had been completed, the clusters were reviewed across the full set of expert feedback to produce the final analysis.

Expert feedback led to clarification of interface relationships, revision of vulnerability narratives, identification of missing elements, or adjustment of cluster boundaries. However, interview comments were not automatically treated as evidence replacing document analysis. They were used to review and refine the interpretation derived from case documentation. Where expert perspectives differed or remained uncertain, these differences were retained where relevant, as they could indicate unresolved assumptions or uncertainty within the developing hydrogen system.

3.3. Analytical Framework

In this thesis, vulnerabilities of hydrogen transport infrastructure are analyzed based on interfaces rather than isolated assets or organizations. For this research, an interface is understood as a boundary or relationship between two interacting entities involving flows of material, energy, or information and/or physical or spatial relations, as well as organizational exchanges such as decisions, responsibilities, approvals, and contractual commitments. The use of this approach is justified because infrastructure performance is determined not only by individual assets and actors, but also by dependencies and feedback relationships between them (Rinaldi, Peerenboom, & Kelly, 2001; Uddin, Campean, & Khan, 2015).

The analytical framework integrates the Interface Analysis Template (IAT), developed by Uddin et al. (2015), with the critical-infrastructure interdependency typology proposed by Rinaldi et al. (2001). The IAT provides a structured way to define interfaces, interaction scenarios, exchanges, requirements, and interaction criticality. For this thesis, the original IAT is adapted and extended to support analysis of vulnerability under uncertainty in emerging hydrogen infrastructure. The extension introduces additional analytical fields covering dominant interdependency type, interface-specific risk, and uncertainty and vulnerability assessment. The typology of Rinaldi et al. (2001) is used to identify the dominant form of interdependency associated with each interface: physical, cyber, geographic, or logical.

Together, original IAT fields and additional fields developed in this thesis allow the framework to move beyond interface description and examine how interdependencies, risks, and uncertainty may contribute to vulnerability. The detailed structure and adaptation of the IAT are presented in Section 3.3.2.

Figure 3.1 shows how the analytical framework fits into the research process. And Section 3.4 describes how it is applied to DHB1.

3.3.1. Conceptualization of Interfaces

Building on the general interface definition introduced above, the analysis distinguishes between **technical interfaces** and **organizational interfaces**.

Technical interfaces are interactions between physical infrastructure components, or between physical components and systems used to measure, monitor, or control them. These interfaces may involve hydrogen or electricity flows, physical connections, pressure and flow conditions, measurement data, alarms, or control signals. For example, the interface between the Bramming-Veerst pipeline and the Mainline Regulator Station (MRS) at Veerst is treated as a technical interface.

Organizational interfaces are interactions between actors involved in planning, regulating, financing, operating, accessing, or coordinating the hydrogen system. These interfaces may involve information, responsibilities, contractual conditions, approvals, market arrangements, operating procedures, or regulatory decisions. For example, the relationship between Energinet and shippers concerning capacity booking and balancing is treated as an organizational interface.

Cross-level relationships are identified analytically when related technical and organizational interfaces are studied together in the cluster analysis. These relationships capture how organizational arrangements may influence technical conditions and, conversely, how technical constraints may require organizational responses. For example, balancing arrangements may influence how linepack and available capacity are used, while technical constraints may require adjustments to balancing rules or access conditions.

3.3.2. Interface Analysis Template and Adaptation

The Interface Analysis Template (IAT) was developed by Uddin et al. (2015) as a systems-engineering tool for systematic identification, description, and analysis of interfaces across different levels of system design. Its role is to make interactions between system elements explicit and to document scenarios, exchanges, functional requirements, and criticality associated with each interface. Uddin et al. (2015) proposed the IAT as a structured template for capturing interface requirements across different system-design levels, from stakeholder-level interfaces to component-level analysis.

In the original IAT, analysis starts with system-interface identification, followed by interaction-scenario definition, interaction-exchange classification, identification of interaction

functions and requirements, and assessment of interaction criticality in relation to a high-level system function (Uddin, Campean, & Khan, 2015). In this thesis, the original structure was adapted to document technical and organizational interfaces identified in Danish Hydrogen Backbone 1 (DHB1). Each row in the adapted IAT represents one defined interface and its principal interaction scenario.

The modified IAT retains nine fields from the original template: C1 and C3–C10. The notation "C" identifies columns in the original IAT and is retained here to maintain consistency with that framework (Uddin, Campean, & Khan, 2015). C1 provides a unique identifier for each interface. C3 documents the description of the generic interaction scenario, while C4 identifies the type of interaction exchange in terms of energy, material, information, spatial, or physical interactions. C5 describes the interaction function and exchange, and C6 and C7 identify the originating and receiving entities. C8 records the technical, operational, contractual, or regulatory requirements associated with the interaction. C9 identifies the interaction's criticality in relation to the relevant high-level function, and C10 defines that high-level function (Uddin, Campean, & Khan, 2015). Interaction criticality is rated on a five-point scale adopted from Pimmler and Eppinger (1994, as cited in Uddin, Campean, and Khan, 2015): +2 indicates an interaction required for functionality; +1, an interaction that is beneficial but not necessary; 0, an interaction that does not affect functionality; −1, an interaction with negative effects that do not prevent functionality; and −2, an interaction that must be prevented to achieve functionality. These ratings concern the interaction's contribution to the high-level function recorded in C10, rather than the probability or severity of failure.

This thesis omits the interaction-code field (C2) used in the original template. In the original IAT, this code is used to differentiate multiple scenarios within a single interface. However, in this study, each row was defined to represent one principal scenario for a particular interface. A separate interaction code would therefore only be necessary if materially distinct scenarios, such as normal operation, planned maintenance, emergency isolation, or off-specification hydrogen handling, were analyzed as separate records for the same interface.

Adaptation of the IAT

To address the research focus on vulnerability under uncertainty, the IAT was extended with five additional fields: C11, dominant interdependency type; C12, interface-specific risk; C13, uncertainty categories; C14, uncertainty level; and C15, vulnerability assessment. In this thesis, these additional fields allow the interface analysis to capture not only the interaction itself, but also the interdependencies, risks, uncertainty conditions, and vulnerability associated with it.

For C11, the interdependency type is defined according to the typology introduced by Rinaldi et al. (2001), which distinguishes physical, cyber, geographic, and logical interdependencies. The dominant interdependency is identified for each interface, while recognizing that secondary interdependencies may also be present.

C12 records the main mechanisms through which an interface could fail, underperform, create operational difficulties, or affect other parts of the system. C13 records the uncertainty

categories relevant to each interface, using the typology presented in Table 3.1. More than one category may be assigned where the interface is affected by distinct sources of uncertainty.

The uncertainty categories used in this study were developed as an analytical typology for the case study. They were derived through an iterative review of the documentary material used in the case study, including project information packages, market and regulatory documents, technical requirements, and relevant literature on hydrogen-infrastructure development.

During the document review, recurring sources of uncertainty were identified and grouped according to the part of the hydrogen value chain or enabling environment to which they primarily relate. This process resulted in seven categories: demand and market uncertainty; supply and resource uncertainty; infrastructure and project-delivery uncertainty; policy and regulatory uncertainty; financing and investment uncertainty; technology-performance uncertainty; and social and political uncertainty. The categories were then applied consistently across the technical and organizational interfaces to support comparison.

Table 3.1: Uncertainty categories used to classify the sources of uncertainty associated with each interface in C13.

Uncertainty category	**Primary focus**
Demand and market uncertainty	Uncertainty concerning demand for hydrogen transport, capacity bookings, tariffs, market participation, and off-take arrangements.
Supply and resource uncertainty	Uncertainty concerning the availability of hydrogen supply, electricity, renewable generation, water, and other required inputs.
Infrastructure and project-delivery uncertainty	Uncertainty concerning infrastructure planning, permitting, construction, commissioning, timing, and coordination across connected assets.
Policy and regulatory uncertainty	Uncertainty concerning legislation, regulatory approvals, market methodologies, tariffs, access rules, and compliance requirements.
Financing and investment uncertainty	Uncertainty concerning investment decisions, funding, cost recovery, commercial commitments, and project economics.
Technology-performance uncertainty	Uncertainty concerning the performance, maturity, integration, reliability, and operational behavior of technical systems.
Social and political uncertainty	Uncertainty concerning stakeholder acceptance, land access, local opposition, political commitment, and public support.

C14 and C15 are based on structured qualitative assessment matrices developed for this thesis. They provide a consistent screening approach for comparing the relative uncertainty and vulnerability of the technical and organizational interfaces included in the analysis, rather than quantifying failure probabilities or providing a quantitative safety assessment. Assessments are based on available documentary evidence and subsequently provide input

to expert review of cross-level cluster interpretations.

Each dimension within C14 and C15 is scored from 0 to 2 for every interface by comparing the available evidence with the assessment criteria. Where evidence falls between two rating categories, the higher score is used as a conservative screening rule. The assessment concerns the planned DHB1 configuration: documented requirements, specified safeguards, and established practices provide the basis for evaluating future protection and control, rather than evidence of completed commissioning. The full criteria, interface-level results, and condensed justifications for each dimension score are presented in Appendix C, with the justifications provided in Section C.3, Tables C.6 and C.7.

Uncertainty Assessment

The uncertainty level in C14 is calculated as the sum of three dimensions:

$$U = E + V + D$$

where E represents **evidence specificity and reliability**. It considers the strength and direct relevance of information supporting interface assessment. A score of 0 indicates that the assessment is supported by direct and specific evidence, such as DHB1 technical specifications, approved methodologies, contractual requirements, detailed design information, or directly applicable standards. A score of 1 indicates that the assessment is partly supported by direct evidence but also relies on reasonable transfer from comparable contexts, such as the Danish methane system, hydrogen standards, or similar infrastructure projects. A score of 2 indicates that limited direct evidence is available and that the assessment depends mainly on preliminary plans, expert judgment, analogies, scenarios, or unresolved assumptions.

V represents **variability of future operating conditions**. It considers the extent to which actual future operation of the interface may differ from available design or planning assumptions. A score of 0 indicates that relevant operating, contractual, or regulatory conditions are defined and expected to remain within a narrow range. A score of 1 indicates that some variation is expected in flows, demand, production, operating schedules, or market behavior, but that the main range and response arrangements are known. A score of 2 indicates that important future conditions are not yet defined or may vary substantially because of uncertainty in project delivery, market uptake, producer behavior, regulation, cross-border arrangements, technology performance, financing, or system configuration.

Lastly, D represents **observability and controllability of deviations**. It considers whether deviations can be detected, diagnosed, and managed in time. A score of 0 indicates a well-defined basis for prompt detection and correction: relevant measurement, alarm, local control, and safe-state functions are documented, responsibility is identified, and established response functions can address the deviation within the required time. A score of 1 indicates that detection or corrective action may be delayed, incomplete, dependent on manual validation, or dependent on coordination between actors. A score of 2 indicates that deviations are difficult to detect, diagnose, or correct because monitoring is incomplete or not yet defined, warning signals may be delayed or ambiguous, or responsibility, authority, and procedures for corrective action are absent or unclear.

The resulting uncertainty score is interpreted as follows: 0–2 represents low uncertainty, 3–4 represents medium uncertainty, and 5–6 represents high uncertainty. A lower total indicates a stronger combined basis in evidence, bounded conditions, and the ability to observe and control deviations, although a gap may remain in one dimension. A higher total indicates greater combined reliance on unresolved assumptions, substantially variable future conditions, or limited ability to identify and manage deviations.

Vulnerability Assessment

The vulnerability assessment in C15 is calculated as the sum of three dimensions:

$$\text{VUL} = F + A + P$$

where F represents the **degree of functional disruption**. It assesses the extent to which a disruption at an interface could reduce DHB1's ability to perform its intended functions, including hydrogen entry, transport, delivery, and the coordination needed to support these functions. A score of 0 indicates a limited local disruption without materially restricting wider system functions. A score of 1 indicates a partial or temporary reduction in function, such as restricted injection, reduced transport capacity, delayed access, or additional operational intervention, without necessarily causing substantial or prolonged loss of a core system function. A score of 2 indicates a substantial or prolonged loss of a core function, such as an inability to maintain an essential pressure transition, deliver hydrogen through the export corridor, or sustain safe transport and system-wide balancing.

For organizational interfaces, functional disruption concerns the access, connection, balancing, and coordination functions they support. Financial or investment effects are relevant insofar as they restrict these functions; they are not scored as separate economic losses. This dimension is distinct from alternative capacity and protection, which assess the available means of maintaining functions or limiting disruption.

A represents **availability of alternative capacity or recovery paths**. It considers whether the relevant system function can be maintained or restored through an alternative. A score of 0 indicates that an effective technical, operational, or organizational alternative is available with little or no material loss of capacity, safety, quality, or service. This may include redundant equipment, an alternative route, reserve capacity, a validated backup system, or a substitute procedure. A score of 1 indicates that a partial alternative exists but involves reduced capacity, reduced flexibility, delayed recovery, additional cost, manual operation, or restricted service. A score of 2 indicates that no feasible alternative can maintain the required function within the relevant response time. The interface therefore acts as a single point of failure for that system function.

Lastly, P represents **adequacy of protection and mitigation measures**. It considers whether preventive and corrective measures can address the identified failure mode. A score of 0 indicates that protection is documented and sufficiently defined: the relevant functions are technically established, responsibility is identified, and the available requirements or design provisions provide a credible basis for timely response. Examples include specified automatic protection, local alarms, isolation, and safe-state functions. A score of 1 indicates

that protection is identified but has important limitations, such as incomplete interface-specific procedures, manual action, inter-organizational coordination, uncertain response time, or performance not established for the relevant integrated scenario. A score of 2 indicates that no credible arrangement is identified, or that major gaps in coverage, responsibility, technical capability, or response time leave the failure mode inadequately addressed.

The total vulnerability score is interpreted as follows: 0–2 represents a less vulnerable interface, 3–4 represents a vulnerable interface, and 5–6 represents a very vulnerable interface. A higher total indicates a greater combined limitation across functional disruption, alternative capacity, and protection. These categories are used for comparative screening across interfaces analysed in this study and should not be interpreted as absolute measures of safety or as probabilities of failure.

3.4. Application of the Analytical Framework

This section describes the process used to apply the analytical framework and construct cross-level vulnerability clusters. It corresponds primarily to Steps 4 and 5 of the methodological process presented in Figure 3.1 and aims to make the analytical path from case evidence and individual interface assessments to final cluster interpretations transparent and traceable.

The aim of this analysis was to examine how technical and organizational interfaces jointly support system functions and how their dependencies may create vulnerability across system levels. In this study, a cross-level cluster is defined as a coherent set of technical and organizational interfaces that support a common system function and are connected through a plausible cross-level mechanism of influence between the two levels. A cross-level mechanism describes the pathway through which a condition at one level influences conditions or responses at the other. This pathway may operate from the organizational level to the technical level, where an organizational arrangement, decision, uncertainty, or disruption affects conditions or operation of a technical interface; or from the technical level to the organizational level, where a technical condition, constraint, or disruption affects decisions, responsibilities, rules, or coordination arrangements. Through these interactions, conditions at one level may create or amplify vulnerability and potential consequences at the other level.

At the time of analysis, a number of technical specifications, operational procedures, connection arrangements, capacity products, balancing strategies, and regulatory methods were still under development. Therefore, cross-level cluster narratives should be understood as informed analytical interpretations of plausible vulnerability mechanisms based on available case evidence and expert review, rather than predictions of future operational outcomes.

3.4.1. Interface Identification and IAT Completion

This section explains how Steps 3 and 4 of the methodological framework shown in Figure 3.1 were applied to DHB1. Step 3 comprised technical decomposition and stakeholder mapping to identify the system elements, actors, and functional boundaries. Step 4 used these outputs

to select, document, and assess interfaces using the adapted IAT.

The technical decomposition used the case documentation to identify pipeline sections, mainline stations, user-connection facilities, external connections, measurement and control systems, and safety functions. Elements were distinguished where their functions, operating conditions, or responsibilities differed, for example at the pressure transition between the new and converted pipeline sections. This helped identify where exchanges and operating conditions had to be coordinated. The resulting decomposition is presented in Section 4.2.

In parallel, stakeholder mapping identified actors involved in development, connection, access, operation, regulation, and cross-border coordination. Actors were identified from the case documents and grouped according to their main role in relation to DHB1. The process was informed by the stakeholder-identification principles discussed by Bryson (2004), rather than by a fixed stakeholder classification. Energinet's Information Package 3 and the European hydrogen-market framework helped clarify the actors' roles and responsibilities (Energinet, 2025c; European Parliament and Council of the European Union, 2024). The stakeholder categories and actors are presented in Section 4.3. The categories are not mutually exclusive, since an actor may perform more than one role. Cross-border involvement was treated as a characteristic of actors and relationships rather than as a separate category.

The stakeholder mapping identified the actors relevant to DHB1, but not every actor was included in a separate interface assessment. Interfaces were selected according to their role in enabling hydrogen production, connection to DHB1, transport through the Danish system, and export towards Germany.

Four criteria guided the selection:

- **Functional relevance:** the interaction supports a function needed for hydrogen production, entry, transport, or delivery through DHB1, or could restrict that function if disrupted.
- **Fit with the study boundary:** the interaction concerns the infrastructure, actors, and activities included within the study's defined scope.
- **Distinct interface:** each IAT record describes a specific connection between components or a specific relationship between actors. The same interaction is not recorded twice simply because it supports more than one system function.
- **Evidence availability:** the available documents provide enough information to identify the interaction and describe its role. Missing details about its final design, agreements, or operation are recorded as uncertainty rather than used alone as grounds for exclusion.

The assessment includes ten technical interfaces, T1–T10, and five organizational interfaces, O1–O5. It does not cover every possible interaction in the hydrogen system. The organizational assessment focuses on Danish actors and their roles in the selected system functions. Gasunie Deutschland is included as the directly connected German network operator, but extending the assessment to the wider German stakeholder network would exceed the scope of the thesis.

Table 3.2 explains why other potential interfaces were not assessed separately and identifies

the selection criterion behind each decision. These exclusions mainly concern the study scope, rather than whether the relationships are relevant to DHB1.

Table 3.2: Potential interfaces not assessed separately.

Potential interface	Reason for exclusion
Energinet–Bundesnetzagentur	The organizational assessment focuses on Danish actors. Gasunie Deutschland is included as the operator directly connecting DHB1 to the German network, but the assessment does not extend to German regulators. German regulatory decisions are considered where they affect the export route, without separately assessing Energinet's relationship with Bundesnetzagentur.
Energinet–Danish Ministry of Climate, Energy and Utilities	The assessment does not examine how the Danish state sets policy or provides funding for DHB1 through its relationship with Energinet. Political support and funding are considered as conditions affecting the project, rather than as a separate interface between the Ministry and Energinet.
Energinet–Evida	No specific connection between Evida's distribution network and DHB1 is included in the configuration assessed. The study examines producer connections to DHB1, rather than a possible future connection between the transmission and distribution networks.

These relationships remain relevant to the wider development of hydrogen infrastructure. Their exclusion means that they are not assessed as separate interfaces within this thesis; it does not mean that their effects are absent or fully represented by another interface.

3.4.2. Cluster Construction

The second stage of the analysis corresponds to Step 5 of the methodological framework shown in Figure 3.1 and moved from individual technical and organizational interface profiles to cross-level vulnerability clusters. The purpose was to identify configurations in which conditions at technical and organizational levels could influence one another and thereby create or amplify vulnerability across the system.

Interfaces were not grouped simply because they were geographically close, belonged to the same asset category, or involved the same organization. A candidate cluster was retained only when included interfaces (1) contributed to a common system function, (2) included both technical and organizational interfaces, and (3) could be connected through a plausible pathway of influence between the two levels. This pathway could operate from the organizational to the technical level, for example where market arrangements, regulatory decisions, or operational rules influence technical operating conditions; or from the technical to the organizational level, where physical constraints or disruptions require changes in rules, responsibilities, coordination, or commercial arrangements.

The cluster-construction process was carried out through the analytical stages summarized in Figure 3.2.

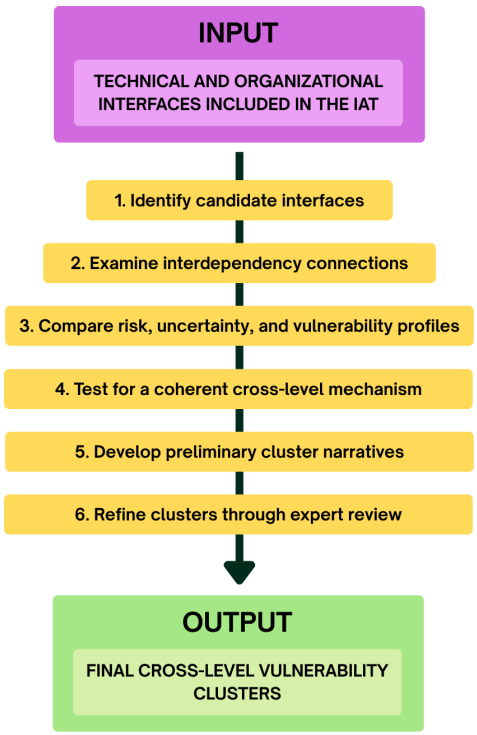

Figure 3.2: Cross-level cluster construction and refinement process.

First, candidate interfaces were identified by comparing completed IAT profiles for shared functional attributes. These could include a common asset, organizational actor, connection point, operational corridor, control function, market process, or higher-level system function. Interaction function, interacting entities, and higher-level function recorded in the IAT were used to identify these initial relationships. At this stage, an interface could contribute to more than one candidate cluster because some assets and organizational arrangements perform several technical, operational, market, or regulatory functions within the hydrogen transport system.

Second, interdependency relationships between candidate interfaces were examined. Physical, cyber, geographic, and logical interdependency categories recorded in the IAT were used to determine how interfaces were connected. Physical interdependencies included hydrogen flow, pressure, linepack, hydrogen quality, and electricity supply; cyber interdependencies included monitoring, measurement, data transfer, alarms, and control systems; geographic interdependencies concerned shared locations or physical environments; and logical interdependencies included rules, contracts, capacity allocation, balancing requirements, connection arrangements, and regulatory decisions. A cluster could contain several interdependency types where they jointly contributed to the same system function.

Third, risk, uncertainty, and vulnerability profiles of candidate interfaces were compared. Additional IAT fields C11–C15 were used to examine whether interdependency type, identified

risks, uncertainty conditions, and vulnerability at one interface could plausibly influence conditions or responses at another. The purpose was not to group interfaces with identical uncertainty or vulnerability ratings, and no combined cluster score was calculated. Instead, comparison was used to trace whether uncertainty, risk, or vulnerability could propagate between connected technical and organizational interfaces.

Fourth, each candidate grouping was examined to determine whether it described a clear cross-level vulnerability mechanism. A grouping was retained where the analysis could explain how organizational conditions could affect technical functions, or how technical constraints could require changes in decisions, responsibilities, or coordination. Sharing an actor, location, or topic was not sufficient.

Fifth, a preliminary vulnerability narrative was developed for each grouping. It described the shared system function, the interfaces involved, the direction of influence, and examples of how vulnerability could develop. These examples were used to explain plausible mechanisms, not to predict future DHB1 outcomes.

The preliminary clusters were reviewed and refined through the expert-review process described in Section 3.2.2. The electricity-PtX and producer-entry clusters were merged because their vulnerability mechanisms were closely related, and examining them together made these relationships clearer. The other three clusters were retained, with revisions to the interfaces included and their interpretation. Appendix F documents the changes from the five preliminary clusters to the four final clusters, including the interfaces added, removed, or redefined.

4

Case context and interface basis: Danish Hydrogen Backbone 1

This chapter provides the empirical basis for the interface analysis of Danish Hydrogen Backbone 1 (DHB1). It translates the project from its planned physical components and the stakeholders involved into a system representation that will serve as a basis to identify the interfaces included in the Extended Interface Analysis Template (IAT).

This chapter has four purposes. First, to define the scope and boundaries of the DHB1 case study. Second, to present the technical decomposition, in order to understand the physical assets, connection points, control, and safety systems relevant to hydrogen transportation. Third, to present the stakeholder analysis that led to the understanding of the organizational actors and their relations affecting access, operations, regulation, and cross-border coordination. Finally, to explain how the technical decomposition and stakeholder analysis provide the basis for identifying and selecting the technical and organizational interfaces examined in Chapter 5.

4.1. Purpose, scope, and system boundary

This research uses Danish Hydrogen Backbone 1 (DHB1) as the case study to examine vulnerability at technical and organizational interfaces in an emerging hydrogen transport system. DHB1 is the first project configuration within the broader development of the Danish Hydrogen Backbone (Energinet, 2025c). DHB1 is planned to connect hydrogen production, which is expected in western Denmark, with the German border and is currently planned to enter operation at the end of 2030 (Energinet, 2025c).

Energinet presents DHB1 as the first planned phase of a broader Danish hydrogen-transmission network, with further infrastructure and connection developments expected to follow as the hydrogen market evolves (Energinet, 2024b, 2024d, 2025c). Consequently, this study treats DHB1 as an initial project configuration rather than as a representation of Denmark's final hydrogen transmission network.

The boundaries of the system used in this study are defined around the conditions required for the hydrogen produced in Denmark to enter DHB1, be transported through the Danish transmission system, and be delivered towards the border with Germany. The case is approached as a socio-technical system, and the boundary includes the technical and physical infrastructure necessary for the hydrogen transportation process, as well as organizational arrangements that shape infrastructure development, connection, access, coordination, and intended operation.

Technically, the scope follows the functional chain from the upstream electricity–PtX–hydrogen-production system through the connection of producers and Danish hydrogen transmission, to cross-border transmission towards Germany. The German connected system is not considered as a separate infrastructure case, but is included as far as the German connected project, namely Hyperlink 3, and related capacities, times, and coordination requirements impact the export function of DHB1. DHB1 is designed primarily as an export system, with regular physical hydrogen transport going south from Denmark to Germany (Energinet, 2025c).

The organizational scope covers actors and relationships which directly impact the functions in this chain. This involves relationships relevant to infrastructure development, physical connection, access to electricity for PtX production, access to hydrogen infrastructure, capacity and balancing arrangements, regulatory procedures and Danish-German coordination. The individual actors, their roles and organizational interfaces emerging from the stakeholder analysis are outlined in Section 4.3.

One of the most relevant features of the case study is the uncertainty. DHB1 has not started commercial operation, and many components of the future infrastructure have not been determined yet and are in the planning, conditional and developing stage. These include the scale and timing of connected hydrogen production, capacity bookings, tariff arrangements, balancing and market procedures, producer connection arrangements, electricity-grid access for PtX facilities, and alignment with the German hydrogen infrastructure. Energinet has described the hydrogen market as immature and has identified uncertainty concerning future production as a central risk for future hydrogen-infrastructure development (Energinet, 2024d). This combination of technical, commercial, organizational, regulatory, and cross-border uncertainty makes DHB1 a relevant case for examining how vulnerabilities may arise at interfaces before the system becomes operational.

The study thus evaluates planned configurations as well as emerging configurations rather than operational performance. Published technical conditions, market configurations, connection processes, tariff structures, balancing mechanisms, and cross-border processes are understood as stipulated conditions, planned configurations, or emerging configurations, but not necessarily as validated operational practice. The vulnerabilities that have been recognized through this thesis are analytical assessments of how dependencies and uncertainties could potentially lead to vulnerability rather than predictions of any particular failures that might occur.

The analysis does not incorporate detailed engineering design, hydraulic modeling, probabilistic safety assessment, or economic valuation of DHB1 and PtX projects. It does not cover the whole German hydrogen network downstream of DHB1, nor does it look into

private commercial configurations of PtX projects. These aspects are only evaluated as far as they influence a specific interface of the DHB1 system boundary.

4.2. Technical system decomposition

Identifying the technical interfaces requires a clear representation of the physical and technical system in which those interfaces are embedded. Interfaces are not present as isolated points; they emerge where hydrogen, pressure, flow, measurements, control signals, operational information, and safety responsibilities are transferred between technical components or across the boundary between connected systems.

Therefore, the technical decomposition identifies the principal components, functions, and technical boundaries that constitute Danish Hydrogen Backbone 1 (DHB1). This provides the technical basis for the subsequent identification and analysis of interfaces.

The decomposition represents the currently planned DHB1 configuration and is organized into six categories: (A) main pipelines, (B) stations on the mainline, (C) connection facilities at user interfaces, (D) cross-border and external network components, (E) measurement, control and data systems, and (F) safety and auxiliary systems.

Electricity supply, PtX production, and internal hydrogen production processes are treated as upstream contextual systems. They are included only where their output or operational behavior may affect hydrogen entry into DHB1. Similarly, the connected German hydrogen network is considered only insofar as it affects the Danish-German interconnection and DHB1's intended export function.

The complete component-level decomposition, including location, function, principal elements, and supporting sources, is presented in Appendix B.

Main pipelines

The main transmission pipelines form the physical transport corridor of DHB1. The planned system consists of two sections: a new hydrogen transmission pipeline between Bramming and Veerst and an existing gas transmission pipeline between Veerst and Frøslev that is planned to be repurposed for hydrogen service (Energinet, 2025c).

The new Bramming–Veerst pipeline is planned as an approximately 41 km transmission section connecting the western hydrogen production area with the central node at Veerst. It is expected to operate at a pressure range of approximately 50–90 barg, with a maximum operational pressure variation of 30 bar. Part of this pressure range is intended to support operational security and system flexibility. Current political project documentation describes the pipeline diameter as approximately 90 cm; however, detailed design remains under development (Danish Energy Agency, 2025; Energinet, 2025c).

The repurposed Veerst–Frøslev pipeline includes 89 km of existing gas transmission infrastructure constructed in 2011 and planned for conversion to hydrogen service. It forms the downstream Danish export section of DHB1 between Veerst and the German border.

Energinet currently identifies an operating pressure range of approximately 35–58 barg and a maximum operational pressure variation of 10 bar for this section (Energinet, 2025c).

The two pipeline sections are treated as separate technical components because they represent different asset configurations and operate within different pressure ranges.

Stations on the mainline

A Pig Launcher and Receiver (PLR) facility is planned at Bramming to support pipeline inspection and maintenance. PLR functions are also incorporated into the station configurations at Veerst and Padborg. These facilities support the insertion and retrieval of pipeline inspection devices and provide associated isolation and depressurization functions (Energinet, 2025c).

The Mainline Regulator Station (MRS) at Veerst is a relevant component because it connects the new Bramming–Veerst pipeline with the repurposed Veerst–Frøslev section. Its principal functions include pressure reduction, flow regulation, overpressure protection, venting, and associated pigging facilities. The site is also prepared for future connection infrastructure and possible eastward network development (Energinet, 2025c).

At the southern end of the Danish corridor, the Mainline Metering Station (MMS) at Padborg performs flow and hydrogen quality measurement before hydrogen is transported towards Germany. It also provides pressure and flow regulation, overpressure protection, isolation, venting, and PLR facilities associated with the southern part of the transmission corridor (Energinet, 2025c).

In addition, six Line Valve stations are planned along the new and repurposed pipeline sections, with spacing not larger than 24 km between each other. Their main purpose is to sectionalize the backbone so that individual pipeline sections can be isolated during maintenance or incidents. The sites are also prepared for the later installation of I/E facilities where required (Energinet, 2025c).

Together, these stations establish the main technical nodes at which pipeline sections interact and where operating conditions can be measured, regulated, isolated, or modified.

Connection facilities at user interfaces

Connection facilities refer to the technical boundary between DHB1 and connected users. This category is composed of the Injection or Extraction (I/E) station owned by Energinet and the user-side connection facilities.

Energinet has identified nine potential connection locations along DHB1: Bramming, Glejbjerg, Veerst, Lunderskov, Sommersted, Agerskov, Klovtoft, Tinglev, and Padborg. I/E stations may be established at these locations depending on concluded connection agreements with individual system users (Energinet, 2025c).

Each I/E station is intended for a specific user and is configured for either hydrogen injection or extraction. The main functions include measurement, regulation, and safety with regard to the transfer of hydrogen between the user facility and DHB1. Energinet is responsible for measurement and validation of hydrogen flow and quality at the I/E station

and expects relevant operational signals and data to be exchanged with connected users (Energinet, 2025c).

The user-side connection facility provides the physical connection between the user's installation and the Energinet I/E station. These facilities will be owned and operated by the user or by a third party acting on the user's behalf. Its technical configuration is specific for each case and will depend on the characteristics of the individual facility and the requirements established during the pre-construction and connection agreement (Energinet, 2025c).

Pressure coordination is significant because the relevant backbone pressure depends on the connection location, hydrogen flow, and available linepack. Energinet currently indicates pressure ranges of approximately 50–90 barg for the planned new-build section and 35–58 barg for the converted section (Energinet, 2025c). Hydrogen entering DHB1 must also meet the applicable quality requirements. Energinet's preliminary framework indicates a minimum hydrogen concentration of 99.5 mol-% and a maximum total inert content of 0.5 mol-%, while the final requirements remain subject to further technical development and standardization (Energinet, 2025c).

Although the developing connections support both injection and extraction, this thesis focuses on injection from hydrogen producers because DHB1 is planned primarily to export hydrogen towards Germany. Potential future extraction, domestic consumption, storage, and other user configurations are recognized as possible future developments but are not analyzed as established elements of the present system configuration.

Cross-border and external network components

The cross-border and external network category contains the technical elements that facilitate DHB1 connection to the infrastructure beyond the Danish transmission network. They include the Danish-German border interconnection point located near Frøslev/Ellund and the linked German hydrogen network, Hyperlink 3.

On the Danish side, hydrogen transported through the repurposed Veerst-Frøslev pipeline reaches the southern part of DHB1, where the Padborg MMS measures the quality of the hydrogen and regulates the flow and pressure to ensure it complies with the requirements to safely enter the German hydrogen network (Energinet, 2025c).

DHB1 is currently designed primarily for physical southbound hydrogen transport from Denmark toward Germany. Energinet also describes the possibility of commercial interruptible northbound backhaul; however, this should not be interpreted as normal physical reverse flow through the Danish backbone (Energinet, 2025c).

Beyond the Danish system boundary, Gasunie Deutschland's Hyperlink 3 represents the external receiving system relevant to this study. The project is intended to extend toward the Danish interconnection at Ellund and provide onward transport through northern Germany. Current Gasunie project information describes a planned transmission capacity of 2.5-4.3 GW, with potential expansion, and development of the relevant corridor during 2028–2031 (Gasunie Deutschland Transport Services GmbH, 2026).

The German network is not decomposed further in this thesis. It is included only where its

availability, capacity, pressure, flow, hydrogen-quality, and operational conditions influence the ability of DHB1 to perform its intended cross-border export function.

Measurement, control and data systems

Measurement, control, and data systems are included in the decomposition because the operation of DHB1 depends not only on physical hydrogen transport but also on reliable information regarding flow, quality, system condition, and operational status.

At the I/E-station level, Energinet is expected to measure and validate hydrogen flow and hydrogen quality. Relevant operational signals and data are also expected to be exchanged between Energinet and connected system users to support the coordinated operation (Energinet, 2025c). Detailed procedures regarding information exchange are expected to be established through individual connection agreements.

Balancing and linepack management are another important information function. Energinet plans to provide shippers with information on the amount of linepack flexibility available in the system, including the overall system balance and each shipper's individual balance position. This information is intended to help shippers manage injections and withdrawals and keep the system within its operating limits. If those limits are exceeded, Energinet may need to apply balancing actions, including controlled cut-off (Energinet, 2025c).

These systems are included because measurement quality, operational visibility, information availability, and control capability influence how the physical infrastructure can be operated and coordinated.

Safety and auxiliary systems

Safety and auxiliary systems were included in the technical decomposition since they support safe operation of the main pipelines, stations, and connection points under normal, maintenance, and emergency conditions by providing protective functions across the DHB1 corridor, including controlled pressure reduction, isolation, and integrity management.

Venting and controlled depressurization systems are planned to be at the PLR stations, MRS Veerst, Padborg MMS, line valve stations, and I/E stations. They allow hydrogen to be depressurized in a controlled manner during startup, shutdown, maintenance, or an incident. Energinet specifies requirements for the location and design of venting or flaring arrangements, including limits intended to prevent unacceptable heat radiation or impacts on adjacent facilities (Energinet, 2025c).

Overpressure protection and isolation systems are located at main stations and connection points. This includes overpressure protection at MRS and MMS facilities, main isolation and sectionalizing valves, and the L/V stations used to divide the backbone into isolatable sections. Their purpose is to protect the transmission infrastructure from unacceptable pressure conditions and to isolate affected sections when required. Energinet also specifies that double isolation and bleed are needed for adjacent PLR configurations (Energinet, 2025c).

Lastly, safety-layout and below-ground equipment requirements apply where hydrogen or PLR facilities are located adjacent to DHB1 installations. These requirements include

minimum separation distances between DHB1 and nearby hydrogen facilities, placement of certain hydrogen-containing equipment below ground where necessary, and positioning PLR hatches so they face away from DHB1 equipment (Energinet, 2025c).

These elements are included in the decomposition because they establish technical conditions under which adjacent equipment, stations, and pipeline sections can interact safely. Their detailed engineering design is outside the scope of the thesis.

4.3. Stakeholder Analysis

The stakeholder analysis was conducted in order to provide an overview of the different actors involved, affected, or able to influence the development and future operation of Danish Hydrogen Backbone 1 (DHB1). While the technical decomposition carried out in Section 4.2 identifies the physical assets, stations, pipeline segments, and control functions that constitute the system, stakeholder analysis identifies the organizations, market actors, public authorities, and wider societal groups connected to those functions.

The objective of carrying out this stakeholder analysis is to identify the principal actor categories, clarify their roles and responsibilities, and establish how they relate to the technical, commercial, regulatory, and cross-border context of the project. This supports the goal of understanding relationships and dependencies among actors, and subsequently, the selection of those who are relevant to the interface analysis.

The stakeholder mapping identified six categories: (1) Transmission and System Operators, (2) Distribution Network Operators, (3) Political and Public Authorities, (4) Regulatory and Market-Governance Actors, (5) Hydrogen Market Participants, and (6) Local Communities and Civil Society Stakeholders.

Transmission and System Operators

Transmission and system operators are responsible for the planning, development, operation, and coordination of the backbone infrastructure and the related system activities. They are important to this case because DHB1 is intended to transport hydrogen from producers in Denmark to users in Germany through a cross-border transmission corridor. The two actors in this category are Energinet, which is responsible for the Danish side of the corridor and for DHB1, and Gasunie Deutschland, which is responsible for the connecting hydrogen infrastructure on the German side.

Energinet is the central Danish infrastructure responsible for developing DHB1 and for the future operation of the Danish hydrogen transmission system. In addition to the infrastructure, Energinet is developing arrangements related to system access, capacity products, balancing, tariffs, connection conditions, hydrogen quality, and operational information exchange (Energinet, 2025c).

Energinet responsibilities extend beyond the physical pipeline. It is expected to operate DHB1 as an entry-exit system, manage system balancing, and coordinate the technical and

commercial conditions under which producers, consumers, and adjacent systems interact with the hydrogen network (Energinet, 2024c, 2025c). Its role as the electricity transmission system operator in Denmark is also relevant because hydrogen production through electrolysis relies on electricity-grid conditions, electricity prices, and the operational interaction between PtX facilities and the electricity system. Therefore, Energinet may interact with the same PtX developers through both electricity-system and hydrogen-system functions.

Gasunie Deutschland is the relevant transmission operator on the German side of the corridor and is developing Hyperlink 3. The project is planned to extend toward the Danish-German interconnection at Ellund and connect the Danish export corridor with the wider German hydrogen infrastructure (Gasunie Deutschland Transport Services GmbH, 2026). Gasunie's current project documentation identifies the company as the pipeline operator for Hyperlink 3.

The relationship between Energinet and Gasunie Deutschland is relevant because the intended operation of DHB1 depends on compatible infrastructure and coordinated arrangements on both sides of the border. This includes technical interoperability, capacity availability, project timing, and eventual operating arrangements. The Danish capacity-allocation framework also requires capacity at the German interconnection to be offered as bundled capacity on both sides of the border (Forsyningstilsynet, 2025).

Distribution Network Operators

Evida is the distribution network operator considered in this analysis. Its expected role is to develop and operate local and regional hydrogen networks that can connect domestic hydrogen producers and consumers. These networks may also create future links between decentralized hydrogen projects and the wider Danish hydrogen system (Evida, 2023, 2024).

In consequence, Evida is relevant to DHB1 because local and regional distribution networks could support the connection of producers and consumers to the broader hydrogen system, especially when hydrogen production or demand is located away from the main transmission route and requires local infrastructure before it can interact with the national network.

However, Evida is not currently assigned responsibility for connecting individual producers directly to DHB1. Under the current DHB1 connection model, the producer owns the connection facility, transports hydrogen to the injection station, and provides the compression required for injection. Energinet owns and operates the injection and extraction station. This distinction is important because Evida's broader role in future hydrogen distribution does not translate into being responsible for the producer connections involving DHB1 (Energinet, 2025c).

Political and Public Authorities

Political and government actors define the strategic, legal, and financial context within which DHB1 can be realized. Their influence comes through political agreements, legislation, project approval, national hydrogen strategies, cross-border commitments, funding decisions, and permitting frameworks.

The Danish Ministry of Climate, Energy and Utilities is the representative of the Danish state in the political development of hydrogen infrastructure. It has been supportive towards the Danish hydrogen strategy and the development of cross-border infrastructure aiming to make the export of renewable hydrogen from western Denmark towards Germany possible. Its role is central because DHB1 depends on political approval, a defined financial framework, and the fulfillment of conditions related to public support, capacity commitments, and project realization (Danish Energy Agency, 2025; Energinet, 2025c).

The German Federal Ministry for Economic Affairs and Climate Action (Bundesministerium für Wirtschaft und Klimaschutz, BMWK) represents the German government's interest in developing a hydrogen economy and securing hydrogen imports. Germany expects to rely on hydrogen imports to meet much of its future demand. Its strategy therefore supports the development of import pipelines and cross-border hydrogen networks. German policy support is important to the development of downstream infrastructure and to the expected demand that underpins the economic case for Danish hydrogen exports (Federal Ministry for Economic Affairs and Climate Action, 2024).

Alongside the two national ministries, a broad category of public authorities and permitting bodies are relevant to both Denmark and Germany. Such entities may include national bodies, local authorities, environmental authorities, planning, and safety authorities. They influence the timelines and viability of the projects through route planning, environmental impact assessments, land use, construction permits, safety regulations, and statutory approvals. In the case of DHB1, the local authorities have been involved regarding the pipeline routing and decision on the placement of stations, taking into account local development, protected areas, built environments, and expected locations of hydrogen production or consumption facilities (Energinet, 2025c). These authorities do not operate the hydrogen network, but their decisions can affect the project's design, approval process, schedule, and overall feasibility.

Regulatory and Market-Governance Actors

Regulatory entities determine the conditions for access to the transmission system and influence how the costs, risks, and responsibilities between the infrastructure operator and market participants are allocated. This role is especially important in a developing hydrogen market, where the market model, tariff structure, and regulatory methodologies are still being established.

The Danish Utility Regulator is the main regulatory body in Denmark relevant to DHB1. It is responsible for approving methodologies associated with the hydrogen transmission system, including tariff methodologies, capacity allocation, short-term capacity reservation, bundled cross-border capacity, balancing, among other arrangements. Several elements of the future DHB1 market framework remain under development and may require regulatory approval before they can be implemented (Energinet, 2025c; Forsyningstilsynet, 2025).

The Danish Utility Regulator has a significant role in the economic regulation of DHB1. It approves the revenue allowance framework for Energinet and checks the methodological basis through which costs are allocated to users of the hydrogen transmission system. This is significant for the project since the developing market is expected to start its operation with a limited number of users and potentially high initial costs for infrastructure. Decisions on

tariffs and cost allocation may, in consequence, affect the commercial conditions faced by shippers, producers, consumers, and potential investors (Energinet, 2025c).

The German Bundesnetzagentur (BNetzA), or German Federal Network Agency, is the equivalent regulatory agency in Germany. It approved the German hydrogen core network in October 2024, within which Gasunie Deutschland is developing Hyperlink 3. Furthermore, BNetzA has also established the ramp-up tariff for the hydrogen core network and plays a central role in the regulatory framework for hydrogen network capacity and market development (Bundesnetzagentur, 2024, 2025).

Because DHB1 depends on a functioning downstream German transport route, German regulatory decisions can affect the availability, cost, timing, and commercial attractiveness of hydrogen transport at the border with Denmark.

Hydrogen Market Participants

The DHB1 market model identifies different formal market roles. These should be considered actor categories rather than individual organizations, as those taking on the particular market roles may vary over time. One legal entity may also perform more than one role, for example by acting as both a hydrogen producer and a shipper (Energinet, 2025c).

A shipper is a market actor that transports hydrogen in DHB1. Shipper's responsibilities include booking the transport capacity and balancing their deliveries and offtakes within the hydrogen system. The shipper role is crucial for the market model since it links commercial transport rights to the operational obligation to maintain a balanced portfolio (Energinet, 2024c, 2025c).

A direct producer is a hydrogen producer that is physically connected to DHB1 through an approved entry point. This category includes Power-to-X developers, electrolyzer operators, and other entities that inject hydrogen into the transmission system. Direct producers are relevant given that their production profile, quality of hydrogen, readiness of connections, data exchange, and reaction to operational challenges can affect the system capability to transport hydrogen in a safe and reliable way (Energinet, 2025c).

The direct consumer refers to the consumer of hydrogen who is directly connected to DHB1. Though DHB1 is intended mainly for export purposes, the direct consumer forms an integral part of the market model as there could be future demand for hydrogen in Denmark. These could include industrial users, energy facilities, or other end users requiring hydrogen delivery through the transmission system (Energinet, 2025c).

A hydrogen storage customer is a market participant who requires hydrogen storage services, including injection into and withdrawal from storage. The term relates to the broader hydrogen market model of Denmark although storage is not included in the immediate DHB1 technical scope. Storage customers may become important if hydrogen storage is developed and connected to the transmission system, hence creating additional flexibility and balancing options (Energinet, 2024b).

Local Communities and Civil Society Stakeholders

Even though civil-society and local stakeholders do not run the operation of DHB1 nor participate directly in the hydrogen market, they may influence project legitimacy, route feasibility, the permitting process, and the project timeline. This category includes landowners, local communities, municipalities, environmental organizations, and other groups whose activities can be affected by construction activities or wider economic and environmental impacts associated with hydrogen infrastructure.

Landowners and local communities are relevant because pipeline routing, stations, connection infrastructure, and construction activities affect land use and the local environment. Their concerns may relate to property access, construction disturbances, landscape impacts, safety, environmental protection, and energy infrastructure location. Energinet has consulted affected municipalities regarding the preliminary route for the hydrogen backbone and municipal land-use interests, including future residential and commercial development (Energinet, 2025c).

Environmental and civil-society organizations could influence the public debate and assessment of DHB1. For instance, Rådet for Grøn Omstilling has raised questions about the economic and climate reasons for building the large hydrogen export pipeline to Germany, pointing out investment risk and alternative uses of public resources (Rådet for Grøn Omstilling, 2025).

The inclusion of these stakeholders does not imply that they have any operational function in the DHB1 project. Instead, it recognizes that the project is embedded in a broader societal context in which legitimacy, environmental concerns, economic criticism, and public support may influence implementation conditions.

5

Interface analysis of DHB1

5.1. Introduction to the interface analysis

In this chapter, an interface-level analysis of the Danish Hydrogen Backbone 1 (DHB1) is presented. The purpose is to examine the most important interactions through which development, access, operation, monitoring, and coordination of the proposed hydrogen transport system take place. Unlike in the case of the physical and organizational level analysis, where each of them was analyzed individually, the interface analysis focuses on the boundaries and interactions between them. In this way, it can reveal both the technical and organizational conditions required to implement DHB1's intended functionality, as well as the vulnerabilities, uncertainties, and dependencies that can emerge at these interaction points.

Interface assessment is conducted through the Extended Interface Analysis Template (IAT) described in Chapter 3. Each interface is represented by one principal interaction scenario and is assessed in relation to the interacting entities, the main exchange, the function of the interaction, applicable requirements, the dominant interdependency type, interface-specific risks, uncertainty conditions, and vulnerability assessment. The complete interface profiles are provided in Appendix A. The uncertainty and vulnerability assessment criteria, together with the interface-level assessment results, are provided in Appendix C.

Sections 5.2 and 5.3 present the technical and organizational interfaces, respectively.

The final section of this chapter summarizes the findings. It identifies patterns in uncertainty, vulnerability, critical dependencies, and potential single points of failure across the technical and organizational interfaces. This synthesis provides the empirical basis for the cross-level clustering undertaken in Chapter 6, where related interfaces are examined together to assess how technical and organizational conditions may interact to create wider vulnerability mechanisms.

5.2. Technical Interfaces

The technical interfaces represent the points where physical infrastructure, control systems, and associated facilities connect to enable hydrogen transport through DHB1. They include exchanges of hydrogen, electricity, pressure, flow, temperature, hydrogen-quality information, measurements, alarms, and control commands. The analysis examines whether these exchanges can support the required operation of the system and whether dependencies, conditions, and failure mechanisms could create vulnerability in the system as a whole.

An overview of the technical interfaces analyzed in DHB1 is presented in Table 5.1. To support interpretation of the individual interfaces, Figure 5.1 shows their location or representative position along the planned DHB1 route. The figure distinguishes the planned new and repurposed pipeline sections, the relevant station types, and the interfaces associated with the upstream electricity supply, PtX production, producer connection, and I/E-station functions.

For clarity, the technical interfaces are organized into two categories according to their role in the hydrogen transport corridor: *Entry and Upstream Supply Interfaces* and *Backbone Transport and Pipeline Operations Interfaces*. Their order reflects the expected flow of hydrogen from a PtX facility through the Danish hydrogen backbone toward the German hydrogen network.

For each category, the analysis describes the main interaction functions, applicable requirements and associated risks, and the resulting uncertainty and vulnerability assessment. The complete extended IAT is provided in Appendix A.



Figure 5.1: Overview of the technical interfaces location along the planned DHB1 route.
Note. The locations shown for T7, T8, and T9 are only representative. The final location, number, and configuration of PtX facilities, producer connection pipelines, and associated I/E stations will depend on the producers that connect to DHB1 and on the final connection agreements. T2, T3, and T6 are represented by coloured labels because these interfaces relate to multiple locations rather than one individual physical point: T2 applies to line-valve stations along the route, T3 applies to I/E stations, and T6 applies to the associated operational data and control exchange between I/E stations and Energinet's SCADA system. The figure is a conceptual representation developed for this study, based on the planned DHB1 configuration.

Table 5.1: Overview of technical interfaces analyzed in DHB1.

Interface ID	Interface	Main function	Dominant interdependency	Uncertainty	Vulnerability
T1	Bramming PLR/main valve station–new Bramming–Veerst pipeline	Enable controlled hydrogen transfer, isolation, pigging, and linepack management at the upstream end of the new pipeline	Physical	Medium	Very vulnerable
T2	DHB1 mainline–line-valve stations	Enable controlled isolation, sectionalization, venting, and depressurization of pipeline sections	Physical	Low	Less vulnerable
T3	DHB1 mainline–I/E stations	Enable controlled hydrogen injection into, or withdrawal from, DHB1 while maintaining mainline operating conditions	Physical	High	Vulnerable
T4	New Bramming–Veerst pipeline–MRS Veerst inlet	Provide inlet conditions for pressure regulation and continued southbound transport	Physical	Medium	Very vulnerable
T5	MRS Veerst outlet–converted Veerst–Frøslev pipeline	Transfer pressure-regulated hydrogen into the lower-pressure converted pipeline	Physical	Medium	Very vulnerable
T6	DHB1 I/E stations–Energinet SCADA system	Support monitoring, flow and quality validation, alarms, and operational control at I/E stations	Cyber	Low	Less vulnerable
T7	PtX hydrogen-production system–producer connection pipeline	Transfer conditioned hydrogen from PtX production into the producer connection pipeline	Physical	High	Vulnerable
T8	Electricity transmission grid–PtX electrolyzers	Supply electrical energy required for hydrogen production	Physical	High	Vulnerable
T9	Producer connection pipeline–DHB1 I/E station	Deliver producer hydrogen to the I/E station for measurement, validation, regulation, and safe injection	Physical	High	Vulnerable
T10	Converted Veerst–Frøslev pipeline–Padborg MMS	Deliver hydrogen to Padborg MMS for measurement, regulation, protection, and onward export toward Germany	Physical	Medium	Very vulnerable

Note. Assessment criteria are defined in Section 3.3.2. The complete extended IAT and sources are included in Appendix A; dimension scores and condensed justifications are provided in Appendix C. Source: Author's analysis based on (American Society of Mechanical Engineers, 2023; Energinet, 2024d, 2025c; European Committee for Standardization, 2023; European Industrial Gases Association, 2023).

5.2.1. Entry and Upstream Supply Interfaces

Entry and upstream supply interfaces have been grouped together because they form the technical chain through which hydrogen becomes available for transport in DHB1. Altogether, they link the electricity supply, hydrogen production, producer connection pipeline, I/E station, the DHB1 mainline, and the operational data and signal exchange required at the I/E station connection point. The interfaces in this category share the same high-level function: enabling the safe, compliant, and controllable entry of hydrogen from PtX production into the hydrogen transmission system.

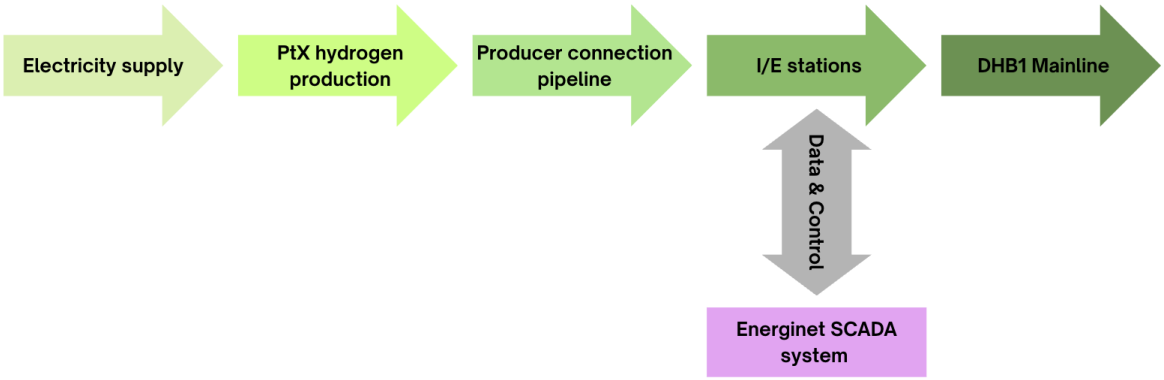

Figure 5.2: Conceptual workflow of entry and upstream supply functions in DHB1.

Figure 5.2 illustrates the functional sequence linking the interfaces grouped in the Entry and Upstream Supply category. T8, T7, T9, and T3 form the pathway through which electricity enables hydrogen production and controlled injection into the DHB1 mainline, while T6 supports the associated data and control exchange between the I/E stations and Energinet's SCADA system.

Main interaction functions

The first interface, T8, "Electricity transmission grid to PtX plant/electrolyzers," represents the supply of electrical energy from the transmission network to electrolyzers and auxiliary equipment. Its function is to supply the power required for hydrogen production. The interface includes the physical connection and supporting equipment, such as substations, transformers, switchgear, cables, protection systems, metering, and operational signals. Physical interdependencies dominate because electrolyzer operation directly depends on electricity supply. However, cyber interdependencies are also present through monitoring, protection, metering, and signalling.

The second interface, T7, "PtX plant/hydrogen production system to producer connection pipeline," concerns the delivery of hydrogen from the PtX production system to the producer-side connection pipeline. Its main function is to transfer conditioned hydrogen from the electrolyzers, compressors, and gas-conditioning system into the service line leading to DHB1. This interface establishes the hydrogen delivery profile from the producer before it reaches the I/E station. Physical interdependencies dominate because hydrogen quality, temperature,

pressure, and flow at the PtX outlet determine conditions within the producer connection pipeline.

The third interface, T9, "Producer service line/connection pipeline to DHB1 I/E station," delivers hydrogen from the producer connection pipeline to the Energinet-owned I/E station. Its purpose is to allow Energinet to receive, measure, validate, regulate, and, where necessary, isolate hydrogen before injection into the DHB1 mainline. This interface is the technical transition point between producer-side facilities and transmission-system infrastructure. It is characterized mainly by physical interdependencies because hydrogen quality, temperature, pressure, and flow delivered from the producer service line determine whether the I/E station can safely receive hydrogen. A secondary cyber dependency is also present because quality validation, alarms, telemetry, and data exchange are relevant to the interface fulfilling its function.

T3, "DHB1 mainline–injection/extraction (I/E) stations," is the interface between the I/E station and the DHB1 mainline. Its function is to enable controlled hydrogen injection into, or withdrawal from, the backbone while maintaining the required operating conditions in the connected pipeline section. This interface has a dominant physical dependency because injection and withdrawal directly affect pressure, flow, linepack, and hydrogen quality in the mainline.

Lastly, T6, "DHB1 I/E stations to Energinet operational data and signal exchange," complements T3 by representing the information exchange required to coordinate injection into, or withdrawal from, DHB1. Energinet states that it will be responsible for measuring and validating hydrogen flow and quality at I/E stations. Connected producers and off-takers are expected to exchange relevant operational data and signals with Energinet to support stable operation on both sides of the connection. T6 therefore has a dominant cyber interdependency because its effectiveness depends on the availability, accuracy, timeliness, and integrity of operational information. Detailed procedures for off-specification hydrogen, operational signals, data exchange, and related processes are expected to be defined in connection agreements (Energinet, 2025c).

Together, these interfaces show that entry into DHB1 is not a single event. It is a series of technical interfaces through which electricity is transformed into hydrogen, hydrogen is conditioned and transported through producer-side infrastructure, and the transmission system verifies that it can be accepted without compromising the operating conditions of the backbone.

Requirements and risks

The interfaces in this category must collectively ensure that hydrogen enters DHB1 under compatible quality, temperature, pressure, flow, monitoring, and control conditions. These requirements become more stringent toward the DHB1 mainline because deviations at the producer side can affect the safe and stable operation of the transmission system.

At T7 and T9, hydrogen must be pre-conditioned before transfer through the producer connection pipeline and acceptance at the I/E station. In addition to the hydrogen-purity requirements presented in Section 4.2, Energinet's preliminary specification requires a

maximum water content of 20 ppm, unodorised hydrogen, and a delivery temperature between 0 and 45°C. It also establishes limits for hydrocarbons, sulphur, oxygen, and other contaminants that could affect the safety, integrity, transport, storage, or use of hydrogen in the system. These conditions are consistent with Energinet's technical reference basis, including CEN/TS 17977 and ASME B31.12 (American Society of Mechanical Engineers, 2023; Energinet, 2025c; European Committee for Standardization, 2023).

The principal risks at T7 arise within the hydrogen-production and conditioning system. Failure of compressors or conditioning equipment, unstable production, rapid flow changes, inadequate drying or quality control, off-specification hydrogen, or insufficient monitoring, alarms, and isolation may prevent hydrogen from reaching the producer connection pipeline with conditions suitable for subsequent transfer. Pressure control, isolation capability, monitoring, and compatible operating conditions are therefore required at the points where hydrogen is transferred between interconnected system components (American Society of Mechanical Engineers, 2023; European Industrial Gases Association, 2023).

T9 is the technical handover from the producer facilities to the transmission system. To operate safely, the hydrogen delivered by the producer must comply with the applicable I/E-station limits for pressure, flow, quality, and ramp rates. The interface also requires clear arrangements for hydrogen-quality measurement, alarms, operational data exchange, cut-off procedures, and incident response. The final specific requirements will be established through technical connection conditions and connection agreements (Energinet, 2024d, 2025c). Therefore, risks arise if the I/E station cannot safely receive, measure, validate, regulate, or isolate the hydrogen. Incompatibility of delivery conditions, inaccurate or delayed quality or flow data, malfunction of inlet valves or regulating equipment, and incomplete alarm or incident-response arrangements may restrict injection, delay identification of abnormal conditions, or prolong restoration of the connection (Energinet, 2024d, 2025c).

T6 supports T9 and T3 by enabling the operational data and control exchange between the I/E stations and Energinet's SCADA system. Energinet is expected to measure and validate hydrogen flow and quality at I/E stations, while connected producers and off-takers must exchange relevant operational data and signals. This information is needed for monitoring, quality validation, alarm management, and management of off-specification conditions.

At T3, injection and withdrawal must remain within the pressure, flow, capacity, and operational limits applicable to the connected DHB1 pipeline section. These conditions differ between the new Bramming–Veerst pipeline and the converted Veerst–Frøslev pipeline, as described in Section 4.2. Daily operating conditions, ramp-rate limits, injection profiles, and cut-off procedures remain subject to final station design and connection agreements (Energinet, 2025c). The associated risk is that injection or withdrawal outside the applicable limits may affect pressure, flow, linepack, and hydrogen quality in the connected mainline section. Relevant risk mechanisms include pressure or flow deviations, off-specification hydrogen, delayed quality validation, inadequate operational information, and insufficiently defined cut-off or isolation arrangements (Energinet, 2025c).

T8 provides the electricity required for electrolysis and auxiliary PtX equipment. Its key requirements concern adequate electricity connection capacity, protection coordination, metering, operational communication, and appropriate restart arrangements. Electricity

interruptions, connection-asset failures, grid congestion, capacity restrictions, curtailment, power-quality disturbances, or inadequate coordination of protection and restart processes may reduce or interrupt hydrogen production. The resulting reduction in hydrogen supply may be partly moderated by plant-side flexibility, compression capability, available linepack, hydrogen storage, or other supply sources. Large electrolyzer facilities may also experience, and contribute to, power-quality effects associated with power-electronic conversion equipment, including harmonic and superharmonic distortion and voltage disturbances (Electric Power Research Institute, 2024; Energinet, 2024a).

Uncertainty and vulnerability

T8, T7, T9, and T3 present a high uncertainty (5/6). This reflects the early development stage of DHB1 and the fact that the final configuration, operating profile, connection arrangements, and performance of future PtX facilities and producer side systems have not yet been established under final DHB1 operating conditions. In the case of T8, uncertainty concerns the availability of electricity, the final connection capacity, the commissioning process, and the performance of the PtX facilities under the specified grid conditions. For T7, the uncertainty concerns the producer-side delivery profile and whether the producer-side systems are capable of providing the required operating conditions. This does not imply that the underlying technologies are unproven; it reflects uncertainty about their final integration, scale, and operating behavior in the DHB1 context (Energinet, 2024d, 2025c).

The mentioned uncertainties at T9 concern the producer-to-transmission transition, including the design of the I/E station, the point of physical handover, specific technical and operational requirements. As for T3, uncertainties concern the final development of the individual I/E stations, the capacity and operating profile of the connected users, and the impact of the future injection/withdrawal patterns on the pressure and linepack in the relevant DHB1 pipeline section. Energinet plans to measure and validate hydrogen flow and quality at I/E stations. However, the arrangement concerning the off-specification hydrogen, operational signaling, data exchange, and alarms, and other issues will be specified through connection agreements (Energinet, 2025c).

In contrast, T6 is assessed as having low uncertainty and lower vulnerability. Direct DHB1-specific evidence states that Energinet will be responsible for measuring and validating hydrogen flow and quality at I/E stations and expects relevant operational data and signals to be exchanged with connected producers and off-takers. The monitoring, control, and data-exchange function is therefore relatively well defined, even though detailed implementation will vary across individual connection agreements (Energinet, 2025c). The business case also identifies procurement and implementation of a SCADA system as part of the DHB project, supporting the relevance of centralized monitoring and control to operational infrastructure (Energinet, 2025a).

T6 has lower vulnerability because a failure of monitoring, control, or operational data exchange at one I/E station would normally have a localized and recoverable effect. It may reduce visibility, delay coordinated response, or require temporary restriction, manual intervention, isolation, or cut-off at the affected connection, but it is not expected to interrupt the complete DHB1 export corridor. Local instrumentation, station protection, isolation

capability, and operating procedures provide partial alternatives and mitigation.

Despite the high uncertainty in this category, T8, T7, T9, and T3 are evaluated as vulnerable rather than very vulnerable because the consequences of disruption are expected primarily to affect a particular PtX facility, producer connection, or local pipeline segment. Isolation and reduction of reliable supply to DHB1 may occur. However, local protection, monitoring, conditioning, isolation, and operational flexibility are expected to provide partial mitigation, and the anticipated presence of multiple producer connections may provide some system-level redundancy for supply.

None of these interfaces is therefore treated as an individual system-wide point of failure. Their combined impact, however, may be greater than the vulnerability of any single interface. If several producer interfaces experience delays, incompatible operating conditions, or reduced production at the same time, the aggregate effect may reduce supply available to the backbone and leave transport capacity underutilized. This cumulative mechanism is examined in Chapter 6.

5.2.2. Backbone Transport and Pipeline Operations Interfaces

Backbone transport and pipeline operations interfaces were grouped because they jointly ensure continuous transportation of hydrogen after it has entered the transmission system through an injection and/or extraction (I/E) station. As illustrated in Figure 5.3, the corridor begins at the Bramming Pig Launcher and Receiver and main valve station, continues through the new Bramming-Veerst pipeline section and through the converted Veerst-Frøslev section, reaching the Padborg Mainline Metering Station (MMS), before onward transfer through the Frøslev–Ellund interconnection to Gasunie Deutschland's Hyperlink 3 system. Their shared high-level function is to maintain safe and continuous hydrogen transport while preserving the pressure, flow, linepack, hydrogen-quality, and isolation conditions required for the Danish export corridor (Energinet, 2025c).



Figure 5.3: Conceptual workflow of backbone transport and pipeline operations in DHB1.

This category includes T1, T2, T4, T5, and T10. Their common feature is a dominant physical interdependency: operating conditions at one interface directly affect the conditions at the next interface. This is relevant because DHB1 is designed as an export corridor with physical southbound flow toward Germany, and the route combines a newly constructed higher-pressure pipeline with a repurposed lower-pressure pipeline (Energinet, 2025c).

Main interaction functions

The first interface, T1, "Bramming PLR/main valve station to new Bramming–Veerst pipeline," manages hydrogen transfer and control at the upstream end of the new pipeline section.

Bramming station includes a pig launcher and receiver, a main valve station, and a vent stack. The function of this interface is to ensure safe continuation, isolation, and controlled depressurization of hydrogen flow during normal operation, commissioning, pigging, maintenance, start-up, shutdown, and incident response. The PLR allows pipeline inspection or cleaning devices to be launched and received, while the main valve and vent stack enable the relevant pipeline section to be isolated and depressurized when necessary. This interface is characterized by physical dependencies because valve position, venting, pressure, flow, temperature, and hydrogen quality at Bramming station influence the operation and linepack of the connected Bramming–Veerst pipeline (Energinet, 2025c).

The second interface, T2, "DHB1 mainline to line-valve stations," relates to the connection between the mainline and line-valve stations distributed along both the new Bramming–Veerst and converted Veerst–Frøslev pipeline sections. Its main function is to provide controlled sectionalization, isolation, venting, and depressurization during maintenance or incidents. Line-valve stations consist of main valves and vent stacks and are installed at intervals of no more than 24 km. The physical dependency is dominant because operation of a line valve changes pressure, flow, and linepack conditions in upstream and downstream pipeline sections. T2 is therefore important for limiting the spatial extent of a disruption and enabling safe restoration of the remaining available pipeline corridor (Energinet, 2025c).

T4 and T5, respectively named "New Bramming–Veerst pipeline to MRS Veerst inlet" and "MRS Veerst outlet to converted Veerst–Frøslev pipeline," form the pressure-transition interfaces between the newly built and converted parts of DHB1. T4 connects hydrogen delivered at higher pressure from the Bramming–Veerst pipeline to MRS Veerst, where pressure and flow are regulated. T5 transfers regulated hydrogen from MRS Veerst to the repurposed lower-pressure Veerst–Frøslev pipeline. These interfaces are closely connected because the ability of the MRS to provide safe and stable outlet conditions depends on the inlet pressure, flow, hydrogen quality, and temperature received through T4. The planned pressure ranges for both pipeline sections are presented in Section 4.2. Physical interdependencies dominate at both interfaces because the inlet and outlet conditions of MRS Veerst determine whether hydrogen can be transferred between the two pressure levels (Energinet, 2025c).

Finally, T10, "Converted Veerst–Frøslev pipeline to Padborg Mainline Metering Station," transfers hydrogen from the converted Danish pipeline to Padborg MMS. Its function is to provide stable inlet conditions for flow measurement, pressure and flow regulation, protection, and isolation before onward delivery toward Germany. Physical interdependencies dominate because pressure, flow, linepack, temperature, and hydrogen-quality conditions arriving through the converted pipeline directly determine the station's ability to receive, regulate, and prepare hydrogen for export (Energinet, 2025c).

Together, these interfaces show that transport through DHB1 depends on more than an uninterrupted pipeline route. Hydrogen must move through a sequence of operational boundaries that enable maintenance, isolation, controlled pressure reduction, flow regulation, linepack management, metering, and protection. T1 and T2 protect the operability and recoverability of the pipeline corridor, while T4 and T5 manage the critical transition between the new higher-pressure and converted lower-pressure sections. T10 prepares controlled pipeline flow for the cross-border export function at Padborg. Consequently, the reliability

of the Danish export corridor depends on the coordinated performance of all five interfaces rather than on the availability of any individual pipeline segment alone (Energinet, 2025c).

Requirements and risks

The interfaces share multiple requirements. Hydrogen must remain within the operating pressure and flow limits presented in Section 4.2, including the different pressure ranges and permitted pressure variations of the new and converted pipeline sections. These pressure limits affect linepack, which is the amount of hydrogen stored in the pipeline and is relevant to transport capacity and operational flexibility (Energinet, 2025c).

Hydrogen quality and temperature are also corridor-wide constraints. The requirements presented in Section 4.2 and Section 5.2.1 apply throughout the corridor. Compliance is important to preserve the integrity of pipeline infrastructure and station equipment and to support interoperability with the downstream system (Energinet, 2025c).

Potential risks at T1 consist mainly of failure or incorrect operation of isolation equipment associated with the PLR, main valve, venting system, and instrumentation. Consequences may limit the ability to safely isolate the beginning of the new Bramming–Veerst section during pigging, maintenance, or an incident. Incorrect sequencing during isolation, venting, start-up, shutdown, or pigging can affect pressure and linepack conditions or leave hydrogen trapped in equipment or isolated pipeline sections. PLR-specific safety arrangements, including inerting during idle periods, double isolation and bleed measures, underground isolation-valve requirements, and controls on venting or flaring, demonstrate that unintended pressurization and hydrogen release are relevant hazards at these facilities (Energinet, 2025c).

At T2, the main risks include a line valve failing to open or close when required, incorrect valve sequencing, uncontrolled depressurization, or leakage from valves, actuators, or vent-stack equipment. These events could delay isolation of an affected segment, increase the portion of pipeline exposed to an incident, reduce transport availability, or create a local hydrogen-release hazard. However, because line-valve stations are distributed along the route, adjacent isolation points can provide partial recovery capability when a particular station is unavailable, although with reduced flexibility and potentially longer restoration times (Energinet, 2025c).

The key risks related to T4 and T5 are associated with the pressure transition at Veerst. At T4, inlet pressure or flow outside the operating range of the station may limit the MRS's ability to maintain regulated conditions for onward transport. At T5, insufficient pressure reduction, incorrect outlet pressure, inappropriate flow-control actions, or problems with regulating valves, instrumentation, isolation equipment, venting equipment, or overpressure protection may affect the integrity and availability of the converted lower-pressure pipeline section. Start-up, shutdown, pigging, and significant changes in upstream supply can create pressure and flow transients, making coordinated control across the MRS boundary essential. No other facility is currently identified as performing this pressure-staging function between the new and converted pipeline sections (Energinet, 2025c).

At T10, pressure or flow outside the operational limits of Padborg MMS may impair the station's ability to regulate conditions for onward export. Off-specification hydrogen may

require restriction, isolation, or corrective action before it can be transferred toward the border. Because Padborg precedes the Danish–German interconnection, maintenance and restoration must be coordinated with both upstream DHB1 operation and downstream cross-border arrangements (Energinet, 2025c).

Uncertainty and vulnerability

T1 is assessed as having medium uncertainty and as very vulnerable. The planned Bramming PLR/main valve station provides a defined operational boundary for the new Bramming–Veerst pipeline, but its final operating philosophy, valve sequencing, commissioning procedures, control logic, and integrated service performance remain to be established. Because no parallel upstream route around this boundary is identified in the initial DHB1 configuration, a sustained loss of T1 could constrain use of the new pipeline section (Energinet, 2025c).

T2 presents low uncertainty and lower vulnerability. Its function and design are relatively well defined, and the distributed network of line-valve stations provides partial recoverability because adjacent stations can support sectional isolation when one location is unavailable. T2 is therefore important primarily as a resilience mechanism that limits the consequences of local faults (Energinet, 2025c).

T4, T5, and T10 are assessed as having medium uncertainty and as very vulnerable. For T4, detailed MRS inlet operating limits, final control settings, and practical operating procedures remain subject to final technical design. For T5, although the planned pressure limits of the converted pipeline are defined in Section 4.2, the final daily operating range, pressure-reduction and flow-control settings at MRS Veerst, and detailed procedures for managing pressure and flow changes during start-up, shutdown, pigging, and significant changes in upstream supply remain to be finalized. At T10, uncertainty concerns integrated operation of the converted pipeline and Padborg MMS, including final border pressure conditions, available export capacity, and detailed operating procedures (Energinet, 2025c).

Their high vulnerability reflects their position as essential, non-redundant points in the DHB1 export route rather than an assumption that the equipment is technically unreliable. MRS Veerst is the only identified facility that manages the pressure transition between the new higher-pressure Bramming–Veerst pipeline and the lower-pressure converted Veerst–Frøslev pipeline. Padborg MMS is the final Danish station that measures and regulates hydrogen before delivery toward Germany. The initial DHB1 configuration does not identify an alternative point of regulation or export route that could take over these functions. Therefore, a prolonged disruption at T4, T5, or T10 could restrict hydrogen transport through the entire southbound export corridor, even where isolation valves, protection systems, monitoring, and control measures reduce immediate safety consequences (Energinet, 2025c).

Overall, this category shows that DHB1's export capability depends on the coordinated availability of its operational boundaries and critical transition points. These dependencies carry forward into the market, balancing, organizational, and cross-border interfaces examined later in the analysis.

5.3. Organizational interfaces

Organizational interfaces focus on the institutional, contractual, regulatory, and operational relationships that enable DHB1 to be developed and used as a hydrogen transmission system. While the technical interfaces in Section 5.2 describe dependencies within technical assets and explain how electricity and hydrogen are physically transferred, controlled, and transported, the organizational interfaces describe how relevant actors coordinate the decisions, responsibilities, conditions, and commitments required for these technical functions to be realized. As shown in the overview of organizational interfaces in Table 5.2, five organizational interfaces are identified: Energinet and shippers, Energinet and direct producers, Energinet and Gasunie Deutschland, Energinet and the Danish Utility Regulator, and Energinet and PtX developers/operators. To facilitate a clear explanation of their different roles, the organizational interfaces are grouped into two categories: *PtX Development and DHB1 Entry*, and *Market, Regulatory, and Cross-Border Coordination*. The complete IAT assessments are included in Appendix A.

Table 5.2: Overview of organizational interfaces analyzed in DHB1.

Interface ID	Interface	Main function	Dominant interdependency	Uncertainty	Vulnerability
O1	Energinet HTNO/DHB1 owner–shippers	Enable transparent, non-discriminatory, and operationally compatible use of DHB1 by shippers, supporting hydrogen transport from production and domestic entry points to consumption and export points	Logical	Medium	Vulnerable
O2	Energinet HTNO–direct hydrogen producers at I/E stations	Enable safe, non-discriminatory, and operationally compatible injection of hydrogen from direct producers into DHB1 through I/E stations	Logical	High	Vulnerable
O3	Energinet HTNO–Gasunie Deutschland/Hyperlink 3	Enable the timely and coordinated realization of a compatible Danish–German hydrogen transport corridor connecting DHB1 with Hyperlink 3	Logical	High	Very vulnerable
O4	Energinet HTNO–Danish Utility Regulator	Enable a transparent, legally compliant, and economically sustainable regulatory framework for access to and use of DHB1	Logical	Medium	Vulnerable
O5	Energinet electricity TSO–PtX developer/operator	Enable timely, transparent, and operationally compatible electricity-grid access for PtX hydrogen-production projects that may supply DHB1	Logical	Medium	Vulnerable

Note. Assessment criteria are defined in Section 3.3.2. The complete extended IAT and sources are included in Appendix A; dimension scores and condensed justifications are provided in Appendix C. Source: Author's analysis based on (Energinet, n.d., 2024b, 2024c, 2024d, 2025b, 2025c, 2026a, 2026b, 2026c; Forsyningstilsynet, 2025; Gasunie Deutschland Transport Services GmbH, 2026).

5.3.1. PtX Development and DHB1 Entry

This category includes O5, which concerns the relationship between Energinet, as electricity transmission-system operator, and PtX developers/operators, and O2, which concerns the relationship between Energinet, as hydrogen transmission-network operator, and direct hydrogen producers connecting to DHB1. The interfaces are grouped because they form the organizational pathway through which a PtX project progresses from electricity-grid connection to hydrogen production and, ultimately, to connection and injection into DHB1, as shown in Figure 5.4.

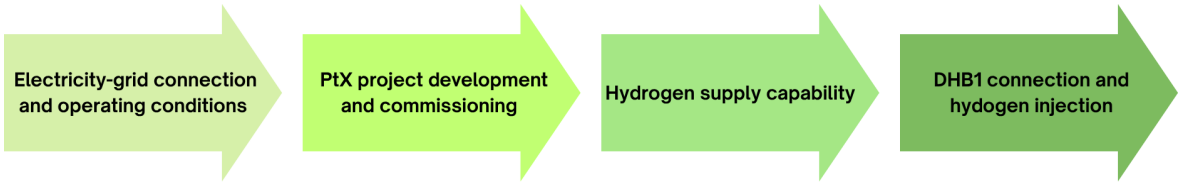

Figure 5.4: Conceptual organizational pathway linking PtX development to hydrogen entry into DHB1.

Figure 5.4 shows how O5 and O2 support the development of a PtX project from electricity-grid connection to hydrogen injection into DHB1. O5 covers electricity-grid connection and operating conditions, as well as PtX project development and commissioning. The transition to hydrogen supply capability links O5 to O2, since a project must be able to produce hydrogen before it can proceed with a DHB1 connection. O2 then governs the arrangements through which the producer connects to DHB1 and injects hydrogen into the transmission system.

This category is relevant because physical availability of DHB1 does not by itself ensure hydrogen supply. A producer must obtain an appropriate electricity-grid connection, develop and commission a PtX facility, and establish the contractual and technical conditions required to connect to the hydrogen transmission system. Delays or uncertainty at either interface can therefore affect the availability and timing of hydrogen supply available for transport through DHB1.

Main interaction functions

O5, "Energinet electricity TSO to PtX developer/operator," concerns the relationship through which PtX developers obtain and use transmission-grid access needed for electrolysis. It includes the connection point, connection capacity, grid-reinforcement needs, delivery timeframe, access conditions, tariffs, protection coordination, metering, information exchange, curtailment communication, reconnection, and restart procedures. Its high-level function is to enable timely, transparent, and operationally compatible electricity-grid access for PtX hydrogen-production facilities that intend to supply DHB1. O5 has a logical interdependency because hydrogen production depends not only on the physical electricity connection but also on grid-access agreements, capacity allocation, reinforcement plans, access-product conditions, curtailment arrangements, tariffs, and clearly defined operational responsibilities (Energinet, 2024a).

O5 is relevant for PtX facilities that may need to operate flexibly in response to electricity-market conditions. Energinet's limited-network-access framework identifies PtX and electrol-

ysis as relevant users for access arrangements in which interruption risk may be accepted in exchange for lower grid charges (Energinet, 2024a). The final choice of access conditions can therefore influence the predictability of electricity supply, the PtX operating profile, and the reliability of hydrogen volumes available for delivery to DHB1.

O2, "Energinet HTNO to direct producers at I/E stations," concerns the organizational relationship that allows direct producers to connect to DHB1 and inject hydrogen under agreed technical, safety, and operational conditions. Energinet is expected to own and operate the I/E station, whereas the producer or a third party is expected to own and operate the connection facility. The connection agreement must allocate responsibilities for connection design, costs, access, maintenance, operational data exchange, alarms, isolation, incident response, curtailment, and return to service. O2 therefore provides the governance framework linking producer-side facilities to Energinet's hydrogen transmission infrastructure (Energinet, 2024d, 2025c).

The high-level function of O2 is to enable safe, non-discriminatory, and operationally compatible hydrogen injection into DHB1. The interface is logically interdependent because a producer's physical access to the system depends on agreed connection conditions, ownership boundaries, technical requirements, capacity arrangements, and operational responsibilities. It directly supports the technical interfaces associated with producer connection pipelines, I/E stations, hydrogen-quality validation, and injection into the DHB1 mainline.

Together, O5 and O2 demonstrate that hydrogen entry into DHB1 depends on two interrelated yet separate governance processes. O5 concerns whether electricity access is adequate for hydrogen production by the PtX project, whereas O2 concerns whether that hydrogen can be connected to and injected into DHB1. These interfaces connect the electricity system, PtX investment decisions, hydrogen-production operations, and the emerging hydrogen transmission system.

Requirements and risks

At O5, Energinet and the PtX developer/operator must establish the electricity-grid connection conditions required to enable hydrogen production. This involves specifying, or establishing the process for determining, the connection point, voltage level, connection capacity, required transmission facilities or grid reinforcements, commissioning sequence, relevant costs, and expected delivery timeline. The applicable arrangement must also specify whether the PtX facility receives full or limited network access and, where relevant, clarify conditions for curtailment, operational flexibility, ramping, and tariff implications. Under limited-access arrangements, a facility may be required to reduce demand or disconnect when necessary to maintain system operation, with disconnection and reconnection processes agreed for the individual connection point. The parties also need to agree on grid and plant protection, metering, data exchange, outage notification, maintenance scheduling, curtailment notifications, reconnection, and restart conditions (Energinet, 2024a).

The key risks at O5 relate to delays in screening and technical assessment of available grid capacity, detailed studies needed to determine the connection point and any reinforcement requirements, permitting, construction, or commissioning. Such delays may postpone electricity access and, consequently, the start of hydrogen production. Further risks arise

where network-access conditions, such as available connection capacity, full or limited access, applicable tariffs, and possible curtailment, remain uncertain, restrictive, or commercially unattractive. Operational risks can also arise from insufficiently defined or poorly coordinated arrangements for protection settings, planned outages, curtailment notifications, reconnection, and restart following an interruption. A further risk is misalignment between the PtX project schedule, electricity-grid connection and reinforcement timeline, and the DHB1 connection and capacity timetable. This may leave electrolyzer capacity without electricity access or leave hydrogen transport capacity underused because the associated PtX facility is not yet able to supply hydrogen (Energinet, 2024a, 2026c).

For O2, the main requirements consist of adequate and timely project information for assessing the connection request, allocating a connection point, and developing the connection solution. This includes project location, injection capacity, expected start of operation, anticipated flow profile, storage arrangements, and other technical characteristics relevant to the interface with DHB1. Energinet's early connection process involves an enquiry and connection-point assignment, followed by a maturation agreement, acceptance of the connection solution, and a connection agreement that can also serve as a construction agreement (Energinet, 2025b, 2025d).

The connected producer must fulfill technical and operational criteria applicable at the DHB1 connection point. These include injection capacity, pressure, temperature, hydrogen quality, ramp-up and ramp-down behaviour, and cut-off conditions, while detailed technical interoperability conditions remain under development (Energinet, 2024b, 2024d). Hydrogen must be supplied at a pressure compatible with the local hydrogen network. Because this pressure can vary with linepack, flow, and location in the network, the producer may need compression to inject hydrogen into DHB1 (Energinet, 2024b). The connection agreement and technical documents should further define division of responsibilities between Energinet and the producer, including cost allocation, ownership and operation of facilities, safety and emergency arrangements, monitoring and control, metering, hydrogen-quality analysis, isolation, and commissioning or start-up procedures (Energinet, 2025b, 2025c, 2025d).

Risks within O2 include delays or disagreements in connection-point allocation, connection-solution development, cost allocation, connection agreements, and completion of construction and commissioning. Risks arise where requirements remain provisional, change during project development, are unclear, or require additional investment by the producer. Insufficiently defined responsibilities for monitoring, control, emergency shutdown, isolation, data exchange, and resumption of injection may also hinder coordinated action when reduction, interruption, or restoration of injection is necessary. These factors may postpone or prevent a producer's effective access to DHB1 even where the PtX facility and physical hydrogen infrastructure are available (Energinet, 2025b, 2025c, 2025d).

Uncertainty and vulnerability

O5 is assessed as having medium uncertainty and as vulnerable. The main uncertainty associated with O5 concerns whether sufficient electricity-grid capacity will be available when the PtX project needs it, whether necessary reinforcements can be approved and completed on time, and which access, tariff, and curtailment conditions will apply. It also depends on

whether the electricity-grid connection timetable can be coordinated with the development schedules of the PtX facility and DHB1. The interface is vulnerable because delays or restrictive access conditions can materially affect a PtX project's ability to produce hydrogen. However, the immediate consequence would normally be that the affected producer is unable or unwilling to commit to delivering hydrogen to DHB1, rather than that DHB1 itself is directly disabled. This may reduce hydrogen volumes available to the network but would not necessarily stop the backbone from operating if other producers remain connected and able to supply hydrogen (Energinet, 2024a).

O2 is assessed as having high uncertainty and as vulnerable. The interface depends on future connection agreements, which will determine the location and configuration of I/E stations, the identity and operating profiles of direct producers, allocation of costs and responsibilities, and detailed procedures for managing hydrogen quality, data exchange, alarms, curtailment, isolation, and return to service. Although Energinet has defined the general connection model and its ownership role at I/E stations, many specific conditions at connection points remain to be established through maturation and connection-agreement processes (Energinet, 2025b, 2025c).

This uncertainty is reinforced by the commercial dependency between producer commitments and realization of DHB1. The project requires market participants acting as shippers or network users, which may include direct hydrogen producers where they also arrange transport, to collectively book at least 0.5 GW of capacity for a minimum of ten years by 1 December 2026 (Energinet, 2026a, 2026b). Although this is an aggregate market requirement rather than an obligation for every individual producer, project viability depends partly on whether producers and other market participants are willing and able to reserve sufficient long-term hydrogen transport capacity. Producers may be reluctant to make binding commitments while their electricity connection, PtX construction, financing, hydrogen offtake, and permitting conditions remain uncertain. At the same time, insufficient capacity commitments may impede project realization. This creates a circular dependency: producers need confidence that transport infrastructure will be available before committing to projects, while Energinet requires credible long-term capacity commitments before infrastructure can be realized.

Overall, this category demonstrates that DHB1 depends on coordinated progress across electricity and hydrogen sectors. O5 affects whether PtX projects can secure electricity access necessary to generate hydrogen, while O2 affects whether hydrogen can enter the transmission system under clear and compatible technical, operational, and commercial conditions. Together, these interfaces influence availability, reliability, and committed volume of supply required to use DHB1 capacity.

5.3.2. Market Access, Regulation, and Cross-Border Coordination

This category includes O1, O4, and O3. O1 concerns the relationship between Energinet, as hydrogen transmission-network operator and owner of DHB1, and the shippers that book and use transport capacity. O4 concerns the regulatory relationship between Energinet and the Danish Utility Regulator, which reviews and approves relevant hydrogen-market methodologies and regulatory arrangements within its legal competence. O3 concerns the cross-border coordination relationship between Energinet and Gasunie Deutschland, which is developing Hyperlink 3 and the connected hydrogen-network infrastructure in Germany. These interfaces are grouped because they provide the organizational and commercial conditions required for Danish hydrogen to be transported through DHB1 and delivered to the German market, as illustrated in Figure 5.5.

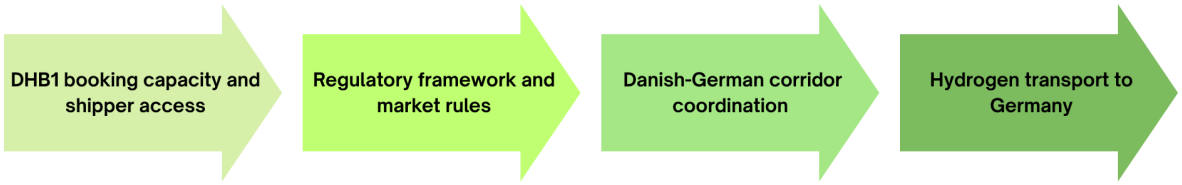

Figure 5.5: Conceptual organizational pathway linking DHB1 market access to cross-border hydrogen transport.

Figure 5.5 shows the functional relationship among O1, O4, and O3. O1 enables shippers to book and use DHB1 capacity, while O4 provides the regulatory framework for capacity allocation, tariffs, balancing, and related market rules. O3 supports coordination between the Danish and German hydrogen systems, including relevant infrastructure, capacity, and border arrangements. Together, these interdependent interfaces enable hydrogen transport from DHB1 to the German network.

These interfaces are important because a physically completed hydrogen pipeline does not itself guarantee that transport can take place. Shippers must obtain capacity rights and operate within applicable market and balancing arrangements; Energinet must have a clear and legally compliant regulatory framework in place; and DHB1 must be coordinated with the connected German infrastructure so Danish hydrogen can enter Hyperlink 3 and reach downstream markets. Delays, regulatory uncertainty, insufficient market participation, or a mismatch between Danish and German development processes may restrict the practical use and commercial value of DHB1 even where physical assets are available (Energinet, 2024d, 2025c).

Main interaction functions

O1, "Energinet HTNO/DHB1 owner to shippers," concerns the relationship through which shippers obtain and use capacity rights in DHB1. In Energinet's market model, a shipper is the market participant responsible for transporting hydrogen through DHB1 and for balancing deliveries and offtakes. A direct producer may also act as a shipper, but these are distinct roles: the direct producer connects physically to DHB1, whereas the shipper arranges transport capacity and manages the corresponding market obligations (Energinet, 2025c).

The high-level function of O1 is to enable transparent, non-discriminatory, and opera-

tionally compatible use of DHB1 by shippers. Energinet expects DHB1 to operate under an entry–exit model, in which capacity is booked at relevant entry and exit points rather than for a specific physical transport path. The model is intended to include domestic production entry, domestic consumption exit, Danish–German export, virtual import from Germany, and a virtual trading point (Energinet, 2024d, 2025c).

O1 is logically interdependent because a shipper's ability to use DHB1 depends on capacity agreements, tariff arrangements, capacity-allocation procedures, nomination and balancing rules, and access to accurate market and system information.

O4, "Energinet HTNO to Danish Utility Regulator," concerns the regulatory relationship through which Energinet develops, submits, and implements relevant hydrogen-market methodologies. The Danish Utility Regulator reviews and decides on methodologies within its legal competence and monitors compliance with the applicable regulatory framework. This relationship covers revenue regulation, tariff methodologies, capacity allocation, congestion management, balancing arrangements, connection-cost allocation, and other conditions governing access to and use of DHB1 (Energinet, n.d., 2024d, 2025c).

The high-level function of O4 is to provide a transparent, legally compliant, and economically sustainable framework for access to and use of DHB1. The interface is logically interdependent because Energinet's capacity-sale process, tariff design, balancing framework, and other market arrangements depend on statutory requirements, methodology development, stakeholder consultation, and, where required, regulatory approval. The regulatory framework is particularly important in an emerging hydrogen market because it determines how costs, risks, and access rights are allocated between the infrastructure operator and market participants (Energinet, 2024d).

O3, "Energinet HTNO to Gasunie Deutschland," concerns the relationship through which Energinet and Gasunie Deutschland coordinate the development of DHB1 and Hyperlink 3 as a cross-border hydrogen corridor. DHB1 is designed primarily as an export system with physical southbound flow towards Germany, while Hyperlink 3 provides the onward German connection to the wider hydrogen network and potential end users (Energinet, 2024d, 2025c; Gasunie Deutschland Transport Services GmbH, 2026).

The high-level function of O3 is to enable timely and coordinated realization of a compatible Danish–German hydrogen transport corridor. The interface is logically interdependent because the value of DHB1's export route depends on compatible infrastructure, capacity, and market arrangements on both sides of the border (Energinet, 2025c).

Together, O1, O4, and O3 show that DHB1 requires more than physical pipeline infrastructure and producer connections. The backbone must also be supported by a functioning market-access model, transparent regulatory arrangements, and coordinated cross-border development.

Requirements and risks

Across O1, O4, and O3, the central requirement is to establish a transparent, non-discriminatory, and coordinated framework through which hydrogen can be booked, transported, regulated,

and transferred from Denmark to Germany. This requires timely information exchange, clear allocation of responsibilities, compatible capacity arrangements, and procedures for managing changes in project scope, market conditions, and operational requirements.

For O1, Energinet must provide shippers with transparent access to DHB1 capacity, relevant tariff information, and market procedures required to book and use capacity. Shippers must meet applicable contractual, booking, payment, and security requirements. Once DHB1 is operational, Energinet must provide relevant arrangements and system information for capacity use, nominations and re-nominations, balancing, and operational restrictions. Shippers must operate within booked capacity and comply with applicable balancing and nomination requirements (Energinet, 2024d, 2025c).

The O1 requirements are intended to support both long-term investment commitments and operational flexibility. Energinet's market material describes long-term capacity products, reservation of capacity for short-term products, firm and interruptible capacity products, and arrangements for secondary capacity under specified conditions (Energinet, n.d., 2025c, 2026c). These arrangements are intended to enable shippers to secure transport capacity while retaining some ability to adjust their capacity position as production, demand, and market conditions change.

The main O1 risks concern insufficient market uptake and the possibility that tariffs, capacity products, contractual terms, or balancing arrangements do not align with commercial and operational needs of shippers and PtX projects. High transport costs, limited flexibility, or long-term commitments may be difficult for shippers to accept when hydrogen production, electricity prices, offtake agreements, financing, or project-delivery schedules remain uncertain. In addition, incomplete or insufficiently tested procedures for nominations, re-nominations, balancing, and system-information exchange may lead to inaccurate flow positions, delayed responses to production changes, increased imbalance exposure, or a greater need for curtailment and balancing actions (Energinet, 2024d, 2025c, 2026c).

O4 provides the regulatory conditions supporting O1 and other DHB1 market arrangements. Energinet must develop, consult on, publish, and submit relevant methodologies for regulatory approval or notification. These methodologies may cover tariffs, capacity allocation, congestion management, balancing, connection-cost allocation, and related access conditions. The Danish Utility Regulator reviews methodologies within its legal competence and oversees Energinet's compliance with the applicable regulatory framework. The purpose is to ensure that market arrangements are transparent, objective, legally compliant, and economically sustainable (Energinet, n.d., 2024d, 2025c).

The most relevant risks at O4 arise from delays or uncertainty in methodology development, consultation, regulatory review, approval, or implementation. Regulatory decisions or later revisions may affect tariff structures, capacity products, balancing obligations, connection-cost allocation, or other access conditions after producers, shippers, and investors have made plans or entered commitments. Uncertainty regarding future tariff levels, allowed revenue, state support, and cost allocation may reduce confidence in capacity booking and investment decisions. A further risk is misalignment between an approved methodology, Energinet's implementation, and terms communicated to market participants, which could lead to administrative delays, disputes, or concerns about unequal treatment (Energinet, n.d., 2024d,

2025c).

O3 extends the market and regulatory framework beyond DHB1 by coordinating it with the connected German hydrogen system. Energinet and Gasunie Deutschland must exchange consistent information on project scope, routing, border-interface design, capacity assumptions, schedules, and material dependencies. They must also establish agreements that allocate responsibilities for development, construction, cross-border capacity coordination, and later operational arrangements. The parties must align Danish and German capacity-booking processes so hydrogen booked for export from Denmark can enter the German system and be transported onward (Energinet, 2025c, 2026a; Gasunie Deutschland Transport Services GmbH, 2026).

The principal O3 risks concern misalignment between the Danish and German sides of the corridor. Different permitting, funding, procurement, construction, commissioning, regulatory, or capacity-sale timelines can result in one system being ready before the other. There is also a risk that Danish export capacity, German entry capacity, and onward German transport capacity do not develop at compatible levels, reducing the volume of hydrogen that can be transported across the border. Delays or disagreements regarding technical design, investment responsibilities, border arrangements, cost allocation, capacity coordination, or changes in project scope may require redesign or postpone the corridor's operation. Because DHB1 is designed primarily to transport hydrogen southward to Germany, these cross-border dependencies are central to whether the Danish backbone can perform its planned export function (Energinet, 2024d, 2025c, 2026c; Gasunie Deutschland Transport Services GmbH, 2026).

Uncertainty and vulnerability

O1 is assessed as having medium uncertainty and as vulnerable. Although the capacity-sale framework, long-term capacity products, and broad entry–exit market model are partly defined, uncertainty remains regarding the final level and structure of tariffs, detailed design of short-term products, practical operation of secondary capacity arrangements, final nomination and re-nomination procedures, balancing framework, and information systems needed to support daily market operation (Energinet, 2024d, 2025c, 2026c). The uncertainty is therefore not primarily about whether DHB1 requires a market-access framework, but about how developing arrangements will operate in practice and whether they will provide sufficient flexibility and predictability for shippers and producers.

O1 is vulnerable because market uptake and effective use of DHB1 depend on shippers' willingness and ability to make capacity commitments and operate within applicable market arrangements. If tariff levels, capacity products, balancing conditions, or contractual obligations are commercially unattractive or operationally incompatible with PtX production profiles, shippers may reduce bookings or use capacity below expected levels. The immediate consequence would normally be reduced utilization, lower tariff revenue, or greater balancing complexity rather than an immediate physical failure of DHB1. However, because transport capacity is central to the commercial rationale of the backbone, persistent weak demand or inadequate market participation could materially affect the long-term economic sustainability of the system.

O4 is assessed as having medium uncertainty and as vulnerable. DHB1 is expected to operate under regulated third-party access, and the Danish Utility Regulator has a central role in approving or overseeing relevant methodologies (Energinet, n.d., 2024d). Important elements of the detailed framework remain under development or subject to regulatory decisions, including tariff methodologies, capacity allocation, balancing arrangements, connection-cost allocation, and the relationship between regulatory approval and future market terms (Energinet, 2024d, 2025c, 2026c). The future price paid by shippers for transport capacity depends on total capacity bookings, interest rates, construction and operating costs, allowed revenue, available state support, and implementation of intertemporal cost allocation (Energinet, 2025c).

O4 is vulnerable because producers, shippers, and investors need clear regulatory conditions before making long-term commitments to DHB1. Arrangements for tariffs, capacity allocation, and balancing are still being developed and, where required, must be approved by the Danish Utility Regulator before they can take effect (Energinet, n.d., 2024d, 2025c). If regulatory decisions are delayed or change significantly, capacity sales and contract negotiations may be postponed, and potential users may be less willing to invest or book capacity. This may also affect producer projects, shipper commitments, financing decisions, and coordination with the German system, even though the regulatory interface is not directly linked to the physical pipeline.

O3 is assessed as having high uncertainty and as very vulnerable. Although DHB1 and Hyperlink 3 have defined routes, capacity-sale processes, and planned development pathways, the final cross-border corridor relies on coordinated delivery of two national projects. Its outcome is affected by capacity bookings, industrial demand, financing, permitting, construction progress, regulatory decisions, and availability of downstream German hydrogen infrastructure (Energinet, 2025c, 2026c; Gasunie Deutschland Transport Services GmbH, 2026).

The high uncertainty score also reflects that, although Energinet and Gasunie Deutschland can monitor project milestones, capacity sales, and market signals, they cannot fully control external conditions. These include permitting and funding decisions, construction timetable on the other side of the border, willingness of producers and off-takers to make long-term commitments, and German downstream network availability. A major mismatch between the two systems could therefore require revised agreements, investment decisions, or project redesign and may delay the corridor.

O3 is very vulnerable because DHB1 is designed primarily to export Danish hydrogen to Germany. If Hyperlink 3, the border interconnection, or necessary German entry and onward-transport capacity is delayed or unavailable, DHB1 may be unable to perform its main Phase 1 function even if the Danish pipeline is completed (Energinet, 2025c; Gasunie Deutschland Transport Services GmbH, 2026). No equivalent alternative is identified in the short term that could provide the same high-volume export route at a comparable scale and time. Other options, such as domestic offtake, shipping, alternative carriers, or future interconnectors, may provide partial alternatives but cannot immediately replace the planned DHB1–Hyperlink 3 corridor.

State support, capacity-sale processes, market dialogue, and planned bilateral agreements

provide some protection by supporting coordination and identifying misalignment. However, these measures cannot guarantee synchronized readiness of the two national systems or secure the market commitments, permits, funding, and construction delivery required for the corridor to operate (Energinet, 2026a, 2026b, 2026c; Gasunie Deutschland Transport Services GmbH, 2026).

Overall, this category shows that DHB1 will work as intended only if market, regulatory, and cross-border conditions develop together. O1 concerns whether shippers can book and use transport capacity in a practical and commercially viable way. O4 concerns whether rules for access, tariffs, balancing, and cost allocation are clear enough to support investment and capacity commitments. O3 concerns whether DHB1 can connect to the German hydrogen network and provide the export route on which the first phase of the project depends. Together, these interfaces influence whether sufficient hydrogen can be transported, whether the backbone can attract enough committed capacity, and whether DHB1 can operate as the planned Danish–German hydrogen corridor.

5.4. Synthesis of interface analysis findings

The interface assessments show that high uncertainty does not necessarily translate to high vulnerability. Table 5.3 summarizes the results and explains the main reasons for the uncertainty and vulnerability classifications.

Table 5.3: Summary of interface assessment results and their main explanations.

Interfaces	Uncertainty	Vulnerability	Explanation of the results
T1, T4, T5, T10	Medium	Very vulnerable	Functions and planned assets are defined, but final operating settings and integrated procedures remain uncertain. Prolonged disruption could interrupt corridor transport because equivalent alternatives are not identified and safeguards cannot fully maintain the function. T4 and T5 concern the same pressure-regulation facility.
O3	High	Very vulnerable	Cross-border readiness depends on project delivery, market commitments, and downstream capacity that neither operator fully controls. Misalignment could prevent the planned export function; no equivalent short-term route is identified, and coordination agreements cannot guarantee simultaneous readiness.
T3, T7, T8, T9, O2	High	Vulnerable	Producer configurations, operating profiles, and connection-specific requirements remain unresolved. Disruption would primarily restrict an individual producer or connection, while local protection, isolation, and operating arrangements are expected to provide partial mitigation. Simultaneous restrictions could nevertheless reduce total hydrogen supply.
O1, O4, O5	Medium	Vulnerable	General market, regulatory, and grid-access processes are established, but detailed terms, outcomes, and timing remain uncertain. Delays or restrictive conditions could limit production, commitments, or capacity use. Existing processes offer partial means of adjustment, but cannot remove dependencies on approvals and agreements.
T2, T6	Low	Less vulnerable	Functions and responsibilities are comparatively well defined. Disruption is expected to remain local and recoverable: adjacent isolation points at T2 and local instrumentation, protection, and operating procedures at T6 provide alternatives or corrective measures, although some operational restrictions may remain.

Chapter 6 examines how these interface-level findings combine through interactions between technical and organizational conditions.

6

Cross-Level Vulnerability Analysis

6.1. From Interface Analysis to Cross-Level Vulnerabilities

This chapter provides a cross-level analysis of Danish Hydrogen Backbone 1 (DHB1), drawing on the interface analysis outlined in Chapter 5. It organizes interfaces that support a shared system function and investigates the dependencies by which vulnerabilities and uncertainty may spread across technical and organizational dimensions.

The clusters were developed using the procedure described in Section 3.4.2. The analysis examines both organizational-to-technical and technical-to-organizational pathways through which uncertainty, constraints, or deviations may spread across the emerging DHB1 system.

Based on the interface analysis, four clusters were developed. Cluster 1 considers how backbone access, tariffs, capacity design, and balancing requirements interact with the physical operating margin available in DHB1. Cluster 2 examines how cross-border coordination shapes export availability and how export constraints require commercial and operational coordination. Cluster 3 considers the upstream relationship between electricity supply, PtX hydrogen production, producer connection infrastructure, and entry into DHB1. Cluster 4 examines the reciprocal relationship between operational information, technical control, and the coordination required to maintain safe backbone operation and respond to deviations.

Table 6.1 identifies the interfaces included in each cluster; their descriptions are provided in Chapter 5. Each cluster section presents the cross-level vulnerability mechanism, summarizes the basis for grouping the interfaces, and develops one or more illustrative vulnerability scenarios. All scenarios are analytical examples grounded in the identified interfaces, project documentation, and expert feedback, not predictions of future events or statements of stakeholder positions. They concern material constraints or coordination problems; they do not imply that every operational deviation requires changes to market or regulatory arrangements.

Table 6.1: Technical and organizational interfaces included in each cross-level cluster.

Cluster	Technical interfaces	Organizational interfaces
Cluster 1	T3, T4, T5, T10	O1, O4
Cluster 2	T4, T5, T10	O1, O3, O4
Cluster 3	T3, T7, T8, T9	O2, O5
Cluster 4	T1, T4, T5, T6, T10	O1, O3, O4

6.2. Cluster 1: Backbone Access, Tariffs, and Balancing

6.2.1. Cross-Level Vulnerability Mechanism

This cluster explores the interdependent relationship between market conditions and the regulatory frameworks that shape access to DHB1, the backbone's commercial feasibility, and the physical operating conditions needed to move hydrogen safely southbound. It assesses how tariffs, capacity-product design, booking obligations, nominations, balancing rules, and the use of linepack affect the development and utilization of DHB1, as well as the operating margin available for hydrogen injection, transport, pressure control, and export.

The mechanism can work in both directions. Market and regulatory settings affect the cost, confidence, and flexibility offered to potential users, which may shape whether they choose to make the capacity commitments required for the project to move forward. After DHB1 becomes operational, these settings also affect the anticipated volume, timing, and variability of hydrogen flows that the physical system must be able to manage safely.

Conversely, the backbone's physical characteristics and operating boundaries influence how much transport capacity can be made available, the reliability with which it can be provided, and the extent to which it satisfies users' operational and commercial requirements. Ongoing or structural constraints involving pressure regulation, flow control, linepack levels, station output, maintenance activities, or export delivery may lower available capacity and flexibility. This may require changes to capacity availability, capacity-product design, nomination and balancing processes, curtailment arrangements, and, where applicable, regulatory methodologies.

The vulnerability arises when market arrangements do not provide a commercially viable basis for users to make commitment decisions, or when the flexibility and service conditions expected by users cannot be aligned with the physical operating margin required for safe and reliable backbone operation. Because several market, operational, and regulatory arrangements remain under development, the final relationship among project viability, shipper flexibility, and physical operating conditions has not yet been fully defined

(Energinet, 2024c, 2024d, 2025c).

Figure 6.1 illustrates the bidirectional vulnerability mechanism. From left to right, market and regulatory arrangements may affect project viability, shipper commitments, and expected

flow profiles. In the reverse direction, physical constraints may affect usable capacity, the value of transport access, and the organizational, commercial, or regulatory arrangements needed to support DHB1.

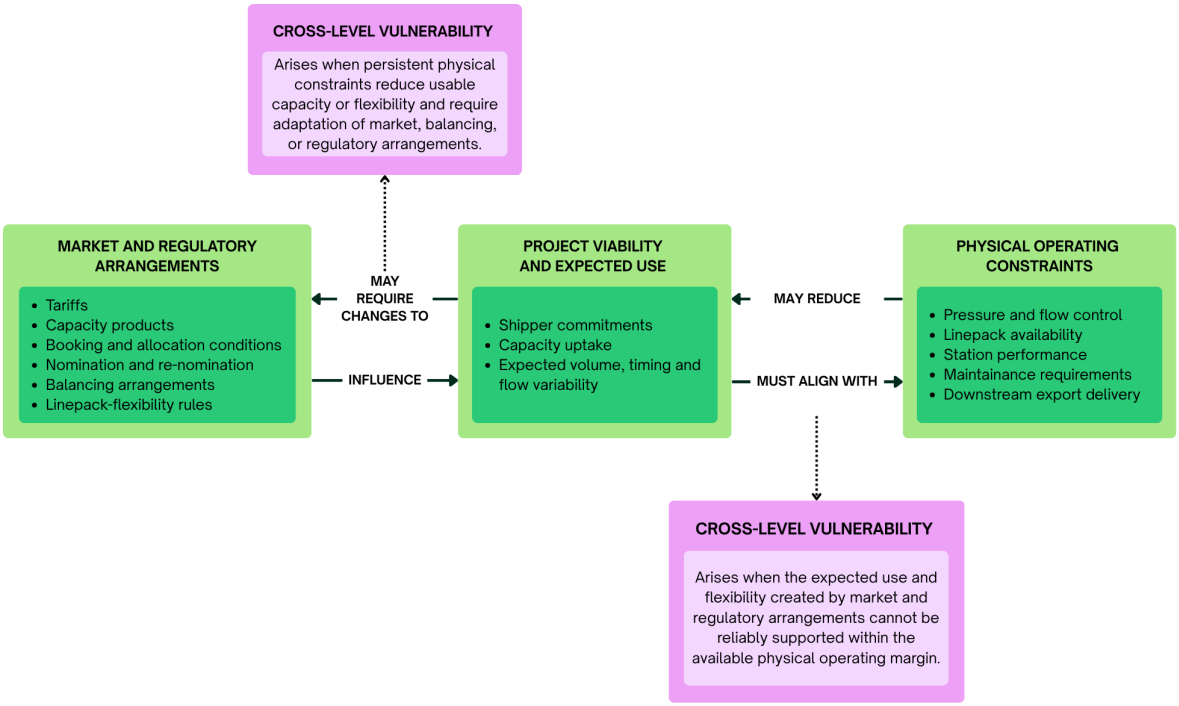

Figure 6.1: Cross-level vulnerability mechanism for backbone access, tariffs, and balancing.
Note. Author's analysis based on the interface analysis in Chapter 5. The figure presents the organizational-to-technical and technical-to-organizational pathways considered in Cluster 1.

6.2.2. Rationale for Cluster Formation

Table 6.2: Rationale for grouping the interfaces in Cluster 1.

Reason for grouping	Explanation
Shared system function	The interfaces jointly support the use of booked transport capacity within DHB1's physical operating limits. Market-access and regulatory arrangements establish the conditions for using capacity, while the technical interfaces enable the corresponding hydrogen entry, pressure regulation, and onward transport.
Dependence between market arrangements and technical capability	Capacity products, nominations, and balancing rules influence the flows and flexibility that the backbone must accommodate. Conversely, pressure limits, available linepack, and station constraints determine how much capacity and flexibility can be offered. These conditions therefore need to be examined together rather than as separate market and technical questions.
Connected uncertainty and vulnerability	Uncertainty in market and regulatory arrangements at O1 and O4, together with uncertainty in future injection profiles at T3, affects the operating demands placed on the backbone. T4, T5, and T10 have limited alternatives for maintaining their functions during disruption. Grouping these interfaces makes it possible to examine whether the service expected by users can be supported by the physical corridor.

6.2.3. Illustrative Vulnerability Scenarios

Market Commitment, Capacity Design, and Sustainable Backbone Use

This scenario considers whether the market arrangements for DHB1 can support the realization of the backbone and its sustainable use after entering operation. It applies the organizational-to-technical pathway shown in Figure 6.1.

Energinet opened the DHB1 capacity sale on 30 January 2026, with capacity requests due by 1 December 2026. Market participants must collectively book 500 MW of entry and exit capacity for at least ten consecutive years from 2031. If this aggregate booking requirement is not met, DHB1 may not proceed towards realization (Energinet, 2026a, 2026b).

Potential users must make long-term commitments while some aspects of the market framework remain under development. Methodologies for long-term capacity products and bundled capacity allocation have been approved, while the methodology for short-term capacity products and allocation remains under development. Detailed arrangements for nominations, re-nominations, balancing, and the use of linepack flexibility will affect how useful and flexible capacity rights are for users of DHB1 (Energinet, 2024c, 2025c; Forsyningstilsynet, 2025).

If prospective users do not agree with the expected tariff, contractual duration, balancing exposure, available flexibility profile, hydrogen-offtake agreement, or financing model, they

may limit or postpone commitments. This can increase the risk of not meeting the minimum booking requirement by December 2026.

Market rules are not the only factor shaping shippers' booking decisions for hydrogen injections and withdrawals. These decisions also depend on the consumption requirements of off-takers. For example, a shipper supplying an industrial customer requiring a stable hydrogen-offtake profile may need more predictable transport access than a shipper serving a customer with more flexible consumption. Hydrogen production also depends on electricity availability and prices; changes in electricity prices may affect when electrolyzers operate and, consequently, the volume and timing of injections into DHB1. Market arrangements influence how such variations are managed, but they do not alone determine underlying consumption and production patterns (Experts 1 and 2, personal communication, August 31, 2026).

Where commitments are made and the backbone is commissioned, market conditions, off-taker demand, and electricity prices may contribute to lower or more variable hydrogen transport volumes over time. If too little capacity is booked, the costs of building and operating the backbone must be covered by fewer users and smaller transport volumes. This can increase the transport cost per unit of hydrogen and make further capacity bookings less attractive. Energinet's sensitivity analysis shows this relationship through a scenario in which 0.5 GW of transport demand and a transport cost of 71 DKK/MWh produced a negative socioeconomic result, whereas higher transport demand improved the expected result (Energinet, 2025a).

Capacity-product design may also affect operational flexibility. If a large share of capacity is offered as firm capacity across most periods, Energinet may have fewer opportunities to isolate pipeline sections, reduce pressure, or undertake planned maintenance without affecting contracted transport. Conversely, planned maintenance windows or temporary reductions in availability could preserve greater operational margin for inspections, sectionalization, depressurization, and maintenance, but may reduce the continuity or flexibility of service available to shippers. This illustrates how capacity commitments and product design may interact with the operating requirements of DHB1 assets.

The vulnerability does not arise only from a high tariff, low demand, or a particular capacity product. It arises if market arrangements do not achieve an appropriate balance between sufficient and commercially viable shipper commitment, the flexibility expected by users, and the operational margin required to maintain the physical backbone safely.

Technical Operating Limits and Market Adaptation

This scenario considers the technical-to-organizational pathway shown in Figure 6.1, in which operating experience may reveal that the flexibility implied by market arrangements cannot be supported reliably within the available physical operating margin.

The DHB1 balancing model depends on the relationship between nominated flows, available linepack flexibility, capacity allocation, and applicable operating limits. However, final connection conditions, operating procedures, market arrangements, and parts of the regulatory framework are still developing (Energinet, 2024c, 2025c). If operation shows that pressure control, flow management, linepack availability, station performance, maintenance

requirements, or export delivery are more constrained than anticipated, the capacity and flexibility offered to shippers may need to be adjusted.

For example, Energinet may need to reserve a larger share of linepack for operational security, reduce the volume of firm capacity offered, revise the balance between long- and short-term capacity products, or modify nomination, re-nomination, curtailment, and balancing procedures. These adjustments could reduce the flexibility or certainty available to shippers, affect the practical value of booked capacity, or change commercial conditions for hydrogen transport.

The relevant vulnerability concerns material, repeated, or prolonged technical constraints that demonstrate a persistent inconsistency between technical capability and the flexibility expected through capacity and balancing arrangements. If such inconsistencies require changes to regulated methodologies, Energinet may need to revise the arrangements and submit them to the Danish Utility Regulator for approval.

This scenario illustrates how physical operating limits can propagate into organizational and regulatory consequences. Technical constraints may require changes to the conditions under which capacity is allocated, nominated, balanced, and priced, thereby affecting both current shippers and the attractiveness of future participation.

6.3. Cluster 2: Cross-Border Export

6.3.1. Cross-Level Vulnerability Mechanism

The main cross-level mechanism examines how Danish hydrogen exports depend on coordinated development and compatible operation of the Danish and German hydrogen systems. Exporting from Denmark requires not only an operational Danish transport route, but also an accessible entry point in Germany, adequate downstream transport capacity, aligned delivery specifications, and agreements that enable market participants to use the corridor as intended.

Organizational decisions and arrangements concerning project timing, capacity commitments, tariffs, booking conditions, nominations, balancing, maintenance, and operating procedures may affect whether the cross-border export route is available and commercially usable when hydrogen reaches the Danish border. If these arrangements are not sufficiently aligned, the Danish export pathway may be physically available while its ability to deliver hydrogen to Germany is delayed, constrained, or commercially impractical.

The relationship may also operate in the reverse direction. A material restriction in the Danish export pathway, or a reduction in German entry or onward transport capacity, may reduce the volume of hydrogen that can be exported. This may require lower producer injections, revised shipper nominations, curtailment or balancing actions, and renewed coordination between the Danish and German transmission-system operators.

Figure 6.2 illustrates the bidirectional mechanism. Organizational and market arrangements may influence the physical availability of the cross-border export route, while a physical

export constraint may generate organizational, commercial, and coordination consequences.

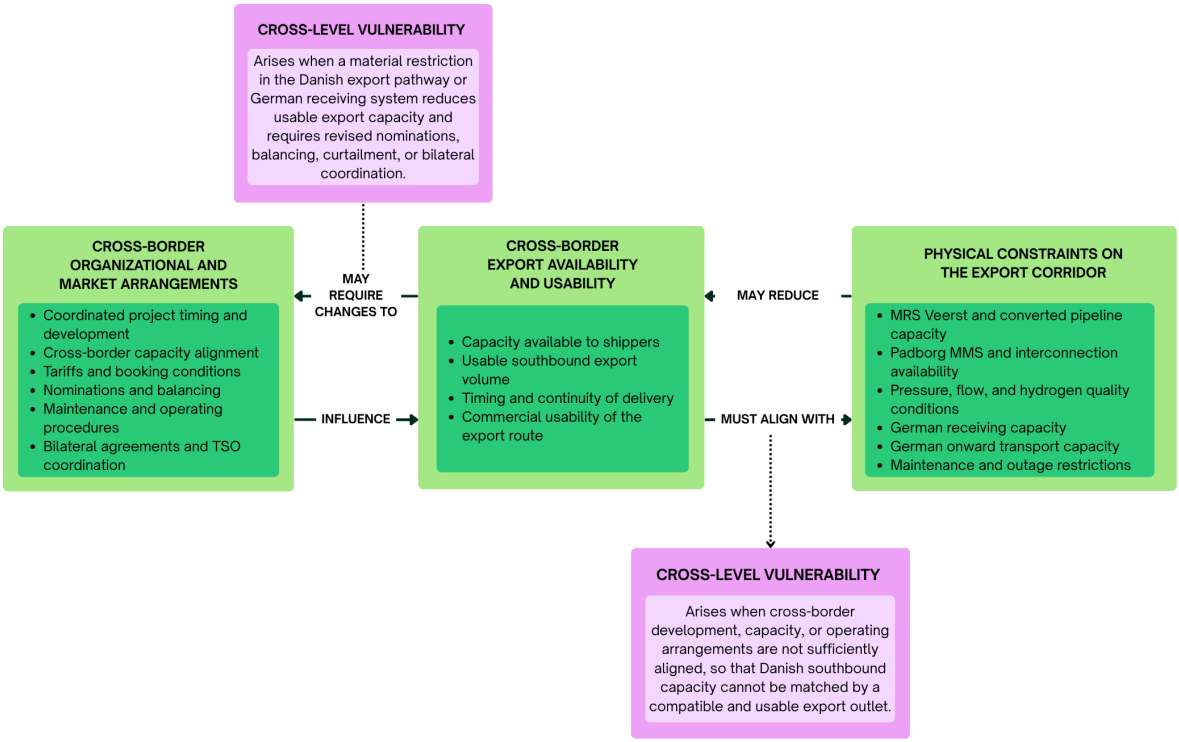

Figure 6.2: Cross-level vulnerability mechanism for cross-border export availability and coordination.
Note. Author's analysis based on the interface analysis in Chapter 5. The figure presents the organizational-to-technical and technical-to-organizational pathways considered in Cluster 2.

6.3.2. Rationale for Cluster Formation

Table 6.3: Rationale for grouping the interfaces in Cluster 2.

Reason for grouping	Explanation
Shared system function	The interfaces jointly support hydrogen export from DHB1 into the German network. Pressure regulation and delivery through the Danish corridor must be matched by available German receiving capacity and the agreements and market arrangements needed to use the connection.
Dependence between cross-border coordination and export capability	Project schedules, capacity arrangements, and delivery conditions on both sides determine whether the Danish route has a usable export outlet. Conversely, a physical restriction in either system can reduce export capacity and require revised nominations, lower injections, and coordinated restoration. Assessing either side alone would miss this dependence.
Connected uncertainty and vulnerability	High uncertainty at O3 concerns coordinated project delivery and downstream availability, while O1 and O4 add uncertainty over the conditions for using export capacity. T4, T5, and T10 are very vulnerable because their functions have limited alternatives. Grouping them reveals how uncertain cross-border arrangements can restrict the value and use of an otherwise available Danish transport route.

6.3.3. Illustrative Vulnerability Scenarios

Synchronized Development, Capacity Alignment, and Export Availability

This scenario applies the organizational-to-technical pathway shown in Figure 6.2. The volume that can be exported through the Danish corridor is constrained not only by capacity of Danish pipelines and stations, but also by capacity available at the Danish-German interconnection and in the downstream German transport system.

Energinet and Gasunie Deutschland are developing DHB1 and Hyperlink 3 as a connected cross-border hydrogen corridor. Expected coordination includes border-route and interface design, development schedules, capacity planning and booking, investment and construction responsibilities, and allocation of those responsibilities. The planned cooperation framework includes a Joint Development Agreement, a Construction Agreement, and a future Operation Agreement for daily cross-border operation (Energinet, 2026a).

These organizational arrangements affect capacity available at the cross-border connection. If the German receiving route, its onward transport capacity, or relevant cross-border agreements are delayed or provide less capacity than expected, export capacity available to Danish shippers may be lower than the physical southbound capacity of DHB1. This does not mean that Energinet is responsible for a German-side restriction; rather, such a restriction may affect capacity available at the interconnection and limit the volume that can be exported from Denmark.

The technical consequence is located in the Danish export corridor. T5 transfers hydrogen from MRS Veerst into the converted Veerst–Frøslev pipeline for continued southbound transport, and T10 transfers hydrogen from that pipeline into Padborg MMS for measurement, pressure and flow regulation, protection, and onward delivery to the Danish-German interconnection (Energinet, 2025c). If less capacity is available at the interconnection, Energinet may need to limit southbound flow through this pathway. Depending on the duration of the restriction, available linepack, connected-producer flexibility, and final operating procedures, this may require reduced hydrogen injections or curtailment upstream.

The underlying vulnerability is therefore a mismatch between physical southbound capacity created in Denmark and lower capacity that may be available at the cross-border outlet. The Danish technical export pathway depends on organizational decisions and project progress in a separately governed German system.

German-Side Export Restriction and Coordinated Danish Response

This scenario applies the technical-to-organizational pathway shown in Figure 6.2. It considers how a planned or unplanned restriction in the German receiving system could reduce export capacity available at the cross-border interconnection and consequently require operational and commercial responses from the Danish system.

Padborg MMS is the final Danish station before onward delivery to the Danish–German interconnection. Energinet's technical documentation states that maintenance, station isolation, start-up, shutdown, and restoration at Padborg must be coordinated with the upstream Danish pipeline and the downstream Danish–German interconnection (Energinet, 2025c).

If a German-side outage, planned maintenance activity, or downstream capacity restriction reduces the volume that can be received from Denmark, this would be reflected in export capacity available at the interconnection. Responsibility for the affected German asset and its restoration would remain with the relevant German transmission-system operator. However, reduced receiving capacity would limit the volume that Danish shippers can deliver through Padborg MMS (Experts 1 and 2, personal communication, August 31, 2026).

The technical restriction on the German side would therefore have organizational consequences in Denmark. Energinet may need to communicate lower available export capacity, coordinate with Gasunie Deutschland on the duration and restoration of the restriction, and apply relevant nomination, balancing, or curtailment procedures. Shippers may need to revise nominations or reduce intended exports. Depending on the duration of the restriction, available linepack, connected-producer flexibility, and final operating arrangements, producers may need to reduce injections into DHB1 or be curtailed.

The absence of a reliable physical alternative strengthens this dependency. DHB1 is designed primarily for physical southbound export to Germany, while capacity from Germany to Denmark is offered as interruptible capacity (Energinet, 2024d, 2025c). Commercial or balancing arrangements may allow a virtual northbound entry from Germany, but this does not create physical reverse-flow capability under normal operation. As clarified by the Energinet experts, the interruptible nature of northbound import capacity makes this

limitation transparent to shippers when they book export capacity; it is therefore not an unrecognized risk in the system design (Experts 1 and 2, personal communication, August 31, 2026). The remaining vulnerability is that, if southbound exports to Germany are restricted, Danish shippers cannot rely on virtual entry or interruptible northbound capacity to physically move hydrogen out of the Danish system.

This scenario identifies a cross-border vulnerability: a technical event outside the Danish system boundary can reduce usable capacity of the Danish export route and require coordinated organizational responses from Energinet, shippers, producers, and Gasunie Deutschland.

6.4. Cluster 3: Electricity Supply, PtX Production, and Producer Entry

6.4.1. Cross-Level Vulnerability Mechanism

The central mechanism examines how the ability to inject hydrogen into DHB1 relies on electricity-grid access, PtX-plant operation, producer connection infrastructure, and operating conditions at the I/E station. Hydrogen can be injected into DHB1 only when the PtX plant has sufficient electricity to produce hydrogen, the producer delivers hydrogen that meets agreed quality, pressure, temperature, flow, and ramp-rate requirements, and the I/E station is available to receive, validate, and inject it into the backbone (Energinet, 2024d, 2025c).

Organizational arrangements concerning grid-connection capacity, reinforcement timing, limited-access or curtailment conditions, producer connection pipelines, ownership boundaries, technical connection requirements, and incident procedures can affect whether hydrogen production can be injected and used by DHB1 as intended. If these arrangements are delayed or insufficiently aligned, electricity capacity or PtX production may be available while hydrogen cannot be delivered to, or injected into, the backbone at the expected volume or time.

The relationship may also operate in the reverse direction. A grid outage, curtailment event, or PtX-plant interruption may reduce hydrogen delivery to the producer connection pipeline and I/E station. If delivery falls outside agreed operating conditions, injection may need to be reduced, suspended, or isolated, requiring notification, curtailment, and coordination for return to service between producers and Energinet. The resulting effect on DHB1 depends on plant-side flexibility, including electrolyzer technology, compression and conditioning equipment, hydrogen storage, producer operating strategy, linepack, and duration and scale of the interruption.

Figure 6.3 illustrates the bidirectional mechanism. Electricity-grid and producer-connection arrangements may affect physical availability of hydrogen entry into DHB1, while electricity-side or PtX-production constraints may reduce hydrogen delivery and require operational and organizational responses.

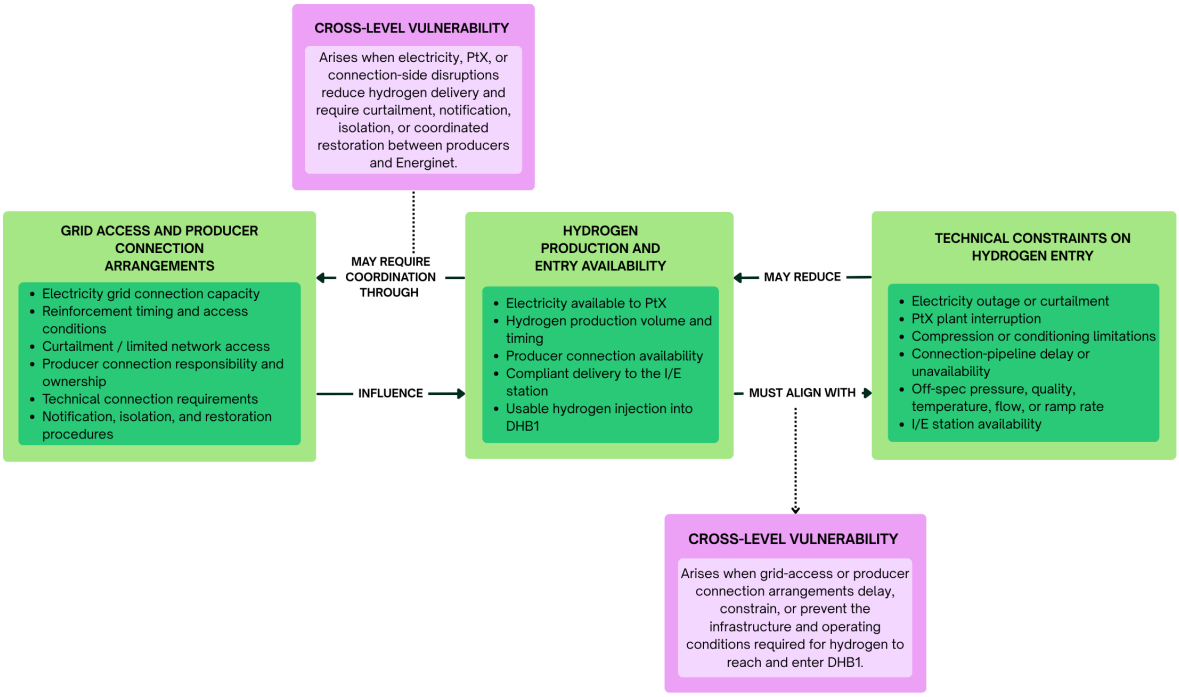

Figure 6.3: Cross-level vulnerability mechanism for electricity supply, PtX production, and producer entry. *Note.* Author's analysis based on the interface analysis in Chapter 5. The figure presents the organizational-to-technical and technical-to-organizational pathways considered in Cluster 3.

6.4.2. Rationale for Cluster Formation

Table 6.4: Rationale for grouping the interfaces in Cluster 3.

Reason for grouping	Explanation
Shared system function	The interfaces jointly enable hydrogen production to become a usable supply to DHB1. Electricity access, PtX operation, producer connection infrastructure, and acceptance at the I/E station must all be available and compatible before hydrogen can enter the backbone.
Dependence between project arrangements and hydrogen availability	Grid-access and producer-connection agreements determine the capacity, timing, responsibilities, and operating conditions of the physical supply chain. Conversely, electricity interruptions or production deviations can require reduced injection and coordinated curtailment or restart. Examining these interfaces together captures how a constraint at one stage can prevent available capacity elsewhere from being used.
Connected uncertainty and vulnerability	High uncertainty at T8, T7, T9, T3, and O2 concerns producer configurations, delivery profiles, and connection-specific arrangements; O5 adds uncertainty over electricity access and its timing. Although individual disruptions primarily affect a producer or connection, their effects can combine along this sequence. Grouping the interfaces allows the analysis to examine whether coordinated readiness and operating conditions support reliable hydrogen entry.

6.4.3. Illustrative Vulnerability Scenarios

Producer Connection Responsibility, Cost, and Delayed Hydrogen Entry

This scenario applies the organizational-to-technical pathway shown in Figure 6.3. It considers how allocation of responsibilities for producer connection infrastructure may affect whether planned PtX production becomes usable hydrogen-entry capacity in DHB1.

A PtX developer requires an electricity-grid connection and a physical hydrogen connection to DHB1. Under the planned connection model, Energinet owns and operates the I/E station, whereas the producer or a third party owns and operates the connection facility leading to that station. The producer is responsible for construction and permitting of the connection pipeline, construction of its PtX facility, and the process required to obtain electricity-grid access (Energinet, 2025b, 2025d, 2026a).

The producer location will likely require a dedicated connection pipeline. A technical safety expert interviewed for this study noted that such pipelines may be approximately 10–15 km long in some cases and may need to cross land owned by several parties or areas subject to environmental and planning restrictions, including protected landscapes. Land rights, route selection, environmental requirements, permitting, pipeline-design requirements, and construction costs may therefore affect the timing and feasibility of the producer connection (Expert 3, personal communication, August 21, 2026).

Producer connection pipelines are also subject to a separate safety and design framework. The Danish Order on the Safety of Pipelines for Gas establishes safety and design requirements for gas pipelines, including hydrogen connection pipelines, and limits the design hoop stress of connection pipelines to 40% of the specified minimum yield strength of the steel (Bekendtgørelse om sikkerhed for rørledninger til gas, 2025). These requirements can influence pipeline design, route selection, documentation, permitting, construction time, and investment cost.

From the perspective of Expert 3, these requirements may be more conservative than necessary for some producer connection pipelines and may increase the cost and complexity of developing the connection to DHB1. This is an expert interpretation rather than a conclusion established by the regulation itself; whether requirements are more conservative than the design basis for DHB1 depends on final technical design and applicable requirements for each pipeline (Expert 3, personal communication, August 21, 2026).

The vulnerability arises from the organizational allocation of connection responsibility. Because the producer or a third party must arrange the connection facility, the physical link between the PtX plant and the DHB1 I/E station depends on a separate set of financing, routing, land-access, environmental, permitting, design, and construction decisions. These decisions are outside delivery of the backbone itself, but they determine whether hydrogen can physically reach the I/E station.

If the producer connection pipeline is delayed, resized, rerouted, or not developed because of cost or permitting constraints, hydrogen produced at the PtX facility cannot be delivered to DHB1, even if the PtX plant has electricity access and DHB1 has entry capacity available. The physical vulnerability is therefore an unavailable or delayed connection link between the production facility and the backbone. This can leave electricity-grid capacity, PtX-production capacity, and DHB1-entry capacity underused, while increasing the producer's cost of hydrogen delivery.

This scenario identifies an organizational-to-technical vulnerability: allocation of connection responsibility can determine whether the physical infrastructure needed for hydrogen entry is completed and available when the wider DHB1 system is ready.

Abrupt Power Interruption, Production Curtailment, and Priority Decisions

This scenario applies the technical-to-organizational pathway shown in Figure 6.3. It considers how an abrupt electricity interruption or prolonged electricity shortage may reduce PtX production and require decisions on safe disconnection, producer curtailment, and restoration.

A grid fault, connection-equipment failure, protection operation, or other unforeseen event may abruptly interrupt electricity supply to one or more PtX facilities. The immediate effect may be a rapid reduction or stoppage of electrolysis and, consequently, lower hydrogen delivery to the producer connection pipeline and I/E station. A technical safety expert identified an abrupt power cut as a potentially critical event because, if the electrical response is not properly designed and coordinated, it may create a surge in the power grid and contribute to a wider electricity-system disturbance (Expert 3, personal communication, August 21, 2026).

The hydrogen-side effect should not be overstated. DHB1 is a large transmission pipeline, and reduced injection from one producer would not necessarily cause an immediate or severe pressure fluctuation. The same expert noted that pressure changes may take hours to become significant, allowing time for manual intervention if automatic controls do not manage the condition. The scale and timing of reduced hydrogen delivery will depend on design and operating characteristics of the affected PtX facility, including electrolyzer technology, plant controls, hydrogen storage, compression and conditioning equipment, producer operating strategy, available linepack in the producer connection pipeline, and duration and scale of the electricity interruption.

The organizational issue becomes more significant when electricity scarcity is prolonged. In this situation, the question is not only whether hydrogen production must be reduced, but which producers should be curtailed, by how much, for how long, and according to which priority criteria. Producers may hold different electricity-connection products, including full or limited network access, and may have different contractual commitments. If curtailment priorities, notification requirements, and restoration principles are not sufficiently clear, a prolonged shortage may create disagreement over allocation of interruption risk and consequences for hydrogen delivery.

This issue is relevant to Energinet's limited-network-access arrangement for electricity consumption. PtX electrolysis is identified as a target group for limited network access, under which users accept interruption risk in exchange for lower grid charges. This does not mean that all future DHB1 producers will have limited access; applicable interruption conditions depend on each producer's electricity-connection agreement (Energinet, 2024a).

On the hydrogen side, a producer affected by a reduction in electricity supply may need to lower or stop delivery to the I/E station. Before injection can resume, the producer must again deliver hydrogen within agreed quality, pressure, temperature, flow, and ramp-rate limits, and the I/E station must be available to receive and validate it. Connection agreements are expected to establish procedures and responsibilities for notification, isolation, curtailment, and return to service between the producer and Energinet (Energinet, 2025b, 2025c, 2025d).

This scenario identifies a technical-to-organizational vulnerability: an electricity-side interruption can reduce hydrogen entry into DHB1, while the consequences depend on facility-specific technical flexibility and on clear, accepted arrangements for curtailment, communication, and restoration.

6.5. Cluster 4: Operational Information, Control, and Coordination

6.5.1. Cross-Level Vulnerability Mechanism

The central mechanism examines how safe operation of DHB1 depends on available, reliable, and shared interpretation of operational information. Energinet must be able to monitor pressure, flow, hydrogen quality, linepack, equipment status, alarms, and cross-border delivery conditions in order to distinguish between normal pipeline variation and a technical fault, measurement problem, shipper imbalance, or restriction at the Danish–German

interconnection (Energinet, 2024c, 2025c).

Organizational arrangements for data validation, alarm management, decision authority, notification, balancing, cross-border communication, and incident procedures influence how operational information is interpreted and acted upon. If these arrangements are incomplete or insufficiently aligned, Energinet may need to operate the physical system more conservatively, for example by reserving additional linepack, reducing flows, restricting injections, or isolating a larger section of the pipeline than the situation actually requires.

The relationship can also operate in the reverse direction. A station malfunction, abnormal pressure or flow condition, suspected hydrogen-quality deviation, valve failure, or loss of reliable operational data may require isolation, depressurization, or restricted operation of part of the backbone (American Society of Mechanical Engineers, 2023; European Industrial Gases Association, 2023). This can require communication with shippers to revise nominations or balancing actions, coordination with Gasunie Deutschland at the interconnection, and agreed procedures for verification and return to service.

Figure 6.4 illustrates the bidirectional mechanism. Operational information and coordination arrangements can affect physical availability and use of DHB1, while a technical abnormal condition can generate organizational, commercial, and cross-border coordination consequences.

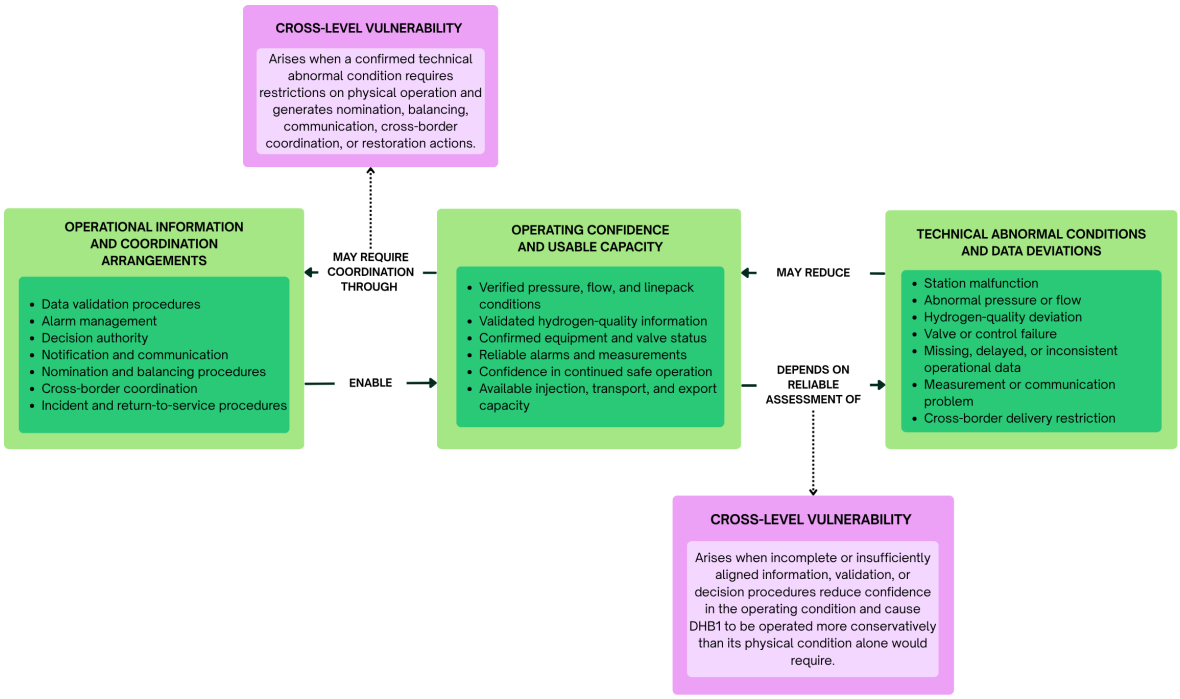

Figure 6.4: Cross-level vulnerability mechanism for operational information, control, and coordination.
Note. Author's analysis based on the interface analysis in Chapter 5. The figure presents the organizational-to-technical and technical-to-organizational pathways considered in Cluster 4.

6.5.2. Rationale for Cluster Formation

Table 6.5: Rationale for grouping the interfaces in Cluster 4.

Reason for grouping	Explanation
Shared system function	The interfaces jointly support the detection, interpretation, and management of operating deviations. Measurements and control capability must be linked to clear responsibilities and communication arrangements so that information about physical conditions can lead to an appropriate response.
Dependence between operational information and coordinated action	Data from T6 and conditions along T1, T4, T5, and T10 inform decisions on injections, flows, isolation, and restoration. O1, O3, and O4 connect these decisions to shipper communication, cross-border coordination, and applicable market methodologies. Technical monitoring alone cannot ensure a coordinated response, while organizational procedures depend on reliable operational information.
Connected uncertainty and vulnerability	T1, T4, T5, and T10 are very vulnerable, while T6 is less vulnerable but supports detection and response. Uncertainty at O1, O3, and O4 concerns procedures, information exchange, and responsibilities. Grouping these interfaces makes it possible to examine how delayed validation or unclear decision authority can prolong restrictions at critical technical interfaces.

6.5.3. Illustrative Vulnerability Scenario

Operational Data, Station Deviation, and Coordinated Flow Management

This scenario illustrates the bidirectional mechanism shown in Figure 6.4. It considers how procedures for validating operational data, managing alarms, and allocating decision authority can affect physical capacity that can be used safely in DHB1. It also shows how a confirmed technical condition can require operational, commercial, and cross-border coordination before normal capacity can be restored.

DHB1's main functions will depend on operational data from stations, pipeline segments, I/E stations, and the Danish–German interconnection. This data includes pressure, flow, hydrogen quality, linepack, valve status, equipment status, alarms, metering, and expected shipper nominations. At I/E stations, Energinet is expected to measure and validate hydrogen flow and quality while exchanging operational data and signals with connected producers and off-takers. Detailed procedures for off-specification hydrogen, alarms, isolation, cut-off, operational communication, and data exchange remain to be defined in connection agreements (Energinet, 2025c).

A deviation between nominated and measured flows, pressure signals, metering values, or station status does not necessarily indicate a physical failure. It may instead result from a shipper imbalance, a producer start-up or shutdown, a measurement or communication problem, an operating change at an I/E station, a pressure-control issue at MRS Veerst,

or a cross-border restriction affecting Padborg MMS. Where data are delayed, incomplete, inconsistent, or not yet validated, Energinet may not immediately be able to identify the cause or determine whether continued operation is safe.

The first direction of the mechanism is organizational to technical. The organizational vulnerability lies in the possibility that Energinet, shippers, producers, and Gasunie Deutschland may lack sufficiently clear or agreed procedures for reconciling conflicting data, confirming the cause of a deviation, deciding who has authority to act, and communicating the resulting restriction. If validation and decision making are delayed, Energinet may need to protect the system by reserving additional linepack, limiting producer injection, reducing flow through MRS Veerst or Padborg MMS, or restricting capacity at an I/E station or the interconnection. The physical system may be undamaged, but its usable capacity becomes lower because the operating condition cannot be confirmed with sufficient confidence.

The mechanism can also operate in the reverse direction. If an abnormal signal is confirmed as a station malfunction, hydrogen-quality deviation, valve failure, or pressure-control problem, Energinet may need to reduce flow, restrict entry, isolate affected equipment, or undertake controlled depressurization while the condition is investigated. Isolation, pressure monitoring, and controlled recommissioning are recognized measures for managing abnormal conditions in hydrogen pipeline systems (American Society of Mechanical Engineers, 2023; European Industrial Gases Association, 2023).

This physical restriction then creates organizational consequences. Energinet may need to publish reduced available capacity, notify affected shippers and producers, apply nomination or balancing procedures, and coordinate with Gasunie Deutschland if export delivery is affected. Before normal flow can resume, affected equipment and pipeline sections must be verified, relevant measurements reconciled, and the return of capacity communicated to relevant actors. The technical condition therefore becomes an organizational issue concerning the scope of restrictions, allocation of capacity, communication of changed operating conditions, and the basis for restoring service.

This scenario identifies an operational vulnerability: usable capacity of DHB1 depends not only on the condition of physical assets, but also on the ability of relevant actors to detect, validate, interpret, communicate, and respond to abnormal information in a coordinated manner.

7

Discussion

This chapter interprets the findings of the interface and cross-level vulnerability analyses in relation to the literature reviewed in Chapter 2 and the research questions in Chapter 1. While Chapters 4–6 identified the technical and organizational interfaces within DHB1 and examined plausible cross-level vulnerability mechanisms, this chapter discusses what these findings imply for understanding and managing vulnerability in emerging hydrogen transport infrastructure.

The discussion is organized in five sections. Section 7.1 interprets the findings in relation to socio-technical systems, infrastructure interdependencies, and vulnerability in emerging hydrogen infrastructure. Section 7.2 discusses the methodological contribution and implications of the Extended Interface Analysis Template used in this study. Section 7.3 considers the practical implications for DHB1. Section 7.4 develops mitigation measures in response to the vulnerabilities identified in Chapter 6. Finally, Section 7.5 discusses the study's limitations and research quality.

7.1. Interpretation of Findings

Vulnerability across Technical and Organizational Interfaces

The results indicate that the vulnerability of emerging hydrogen transport infrastructure cannot be regarded merely as a feature of individual physical assets or of individual organizations. On the basis of the DHB1 case, it can be seen that vulnerability arises out of the interaction between technical operating conditions, organizational structures, market commitments, the progress of regulatory development, and cross-border coordination. The four groups identified in Chapter 6 show that DHB1's ability to carry out its intended function relies on circumstances which go beyond the physical pipeline itself: users must commit to capacity; producers must obtain electricity and develop facilities and connection infrastructure; market and balancing arrangements must be adequately defined; and the Danish system must be linked to an available and compatible German export route.

This finding supports the socio-technical perspective discussed in Section 2.1. DHB1 is not just a pipeline corridor through which hydrogen can be transported once construction is complete. Its functionality depends on a broader configuration of infrastructure, actors, rules, market arrangements, knowledge, and investment decisions. In this configuration, technical and organizational interfaces are not independent layers of the system. Organizational decisions concerning capacity allocation, connection conditions, tariffs, operational procedures, and cross-border agreements may shape the availability and use of physical infrastructure. Conversely, physical constraints related to pressure management, hydrogen quality, linepack, station availability, metering, or export capacity may require changes in market arrangements, operating procedures, contractual conditions, and coordination between organizations.

The findings also reinforce the critical-infrastructure perspective of Rinaldi, Peerenboom, and Kelly (2001). The mechanisms identified encompass physical, cyber, and logical interdependencies that converge at specific interfaces. Physical interdependencies are evident in the relationships among electricity availability, PtX operation, hydrogen production, injection conditions, pressure regulation, linepack, and southbound export. Cyber interdependencies manifest in the reliance on measurements, alarms, SCADA systems, communication, and the capacity to detect and respond to deviations for safe operation. Logical interdependencies are present in the market, regulatory, contractual, and cross-border arrangements that define system access, operational conditions, and management of deviations or constraints. The principal contribution of these findings is to demonstrate that such interdependencies do not remain isolated categories in practice. Instead, they interact within the same operational corridor and collectively influence the availability, flexibility, and resilience of DHB1.

Coordination of Disruptions across Levels

The four clusters further illustrate that cross-level vulnerability is bidirectional. One direction extends from organizational arrangements to technical conditions. For instance, capacity products, tariffs, booking commitments, balancing rules, electricity-grid access, producer-connection responsibilities, and cross-border coordination can determine whether hydrogen is produced, injected, transported, and delivered as intended. The opposite direction extends from technical conditions to organizational consequences. Restrictions in electricity supply, producer-side infrastructure, pressure regulation, station availability, control-system capability, or German receiving capacity may require reduced injections, revised nominations, balancing actions, curtailment, commercial communication, or renewed coordination among relevant actors. Vulnerability thus does not arise solely from an initial technical or organizational disruption. It may emerge when a condition at one level requires a response at another, but the **necessary responsibilities, information, flexibility, or procedures are insufficiently established**.

This finding aligns with the literature on cascading effects in interdependent networks. Buldyrev et al. (2010) show conceptually that a disruption in one interconnected system may generate effects beyond the initially affected component or network. The present study does not model cascading failures quantitatively and does not claim that the identified mechanisms will lead to system-wide collapse. However, the analysis identifies plausible pathways through which a local constraint could produce wider consequences. For example,

a restriction on the German receiving side may reduce usable export capacity in Denmark and subsequently affect shipper nominations, producer injections, curtailment decisions, and linepack use. Similarly, a sudden power interruption may affect PtX production, hydrogen delivery to the I/E station, and decisions regarding safe disconnection, restart, and allocation of available electricity capacity. These mechanisms illustrate that the relevant concern is not only whether an individual asset fails, but whether the system can absorb, detect, coordinate, and recover from deviations across its connected technical and organizational interfaces.

The qualification concerning pressure response in Cluster 3 is discussed in Section 6.4. It shows that vulnerability depends on the characteristics and operating margin of the technical system, rather than following automatically from the existence of an interdependency.

Misaligned Project Readiness and Commitments

A further interpretation is that **alignment and timing** are important sources of vulnerability in the current development stage, rather than a single identified technical failure mode. The clusters show that DHB1 depends on several projects and decisions developing in parallel: hydrogen producers must mature and finance PtX facilities; electricity-grid and hydrogen-connection infrastructure must be available; shippers must commit to capacity; regulatory and market arrangements must be finalized; and downstream German infrastructure and demand must be available when the Danish corridor enters operation. The study's expert feedback describes this as a **project-on-project** risk: producers require credible transport capacity and German off-take before making final investment decisions, while the realization and use of the backbone depend on sufficient producer and shipper commitments.

The alignment problem is significant because uncertainties assessed separately in Chapter 5 can reinforce one another across system levels. Uncertainty regarding tariffs, capacity conditions, and German off-take may delay shipper commitments, and this may affect producer investment decisions, reduce expected hydrogen volumes, and weaken the commercial basis for DHB1. Vulnerability therefore arises not from one uncertainty in isolation, but from mutually dependent decisions being postponed while each actor waits for credible commitments from others.

This pattern reflects the information, incentive, and synchronization problems identified by Westphal et al.(2023). Information problems arise where future demand, tariffs, technical requirements, and downstream conditions remain unresolved. Incentive problems arise where individual actors bear connection, development, or operating costs while system-level benefits depend on actions by others. Synchronization problems arise because infrastructure, PtX production, market access, regulatory approval, and German off-take must become available within compatible timeframes. Emerging hydrogen infrastructure is therefore not only a construction challenge, but also a coordination challenge involving simultaneous technical development and commercial commitment.

Limited Alternatives and Response Capability

The study also makes a distinction between limited physical alternatives and insufficient organizational alternatives. Several DHB1 functions along the southbound route are initially non-redundant, which means that a restriction can have an effect that goes beyond the immediate asset; nevertheless, the extent of the consequences will depend on whether arrangements for curtailment, nomination, maintenance, restoration, data-exchange, and communication are in place. **Physical redundancy and organizational preparedness are complementary** since limited physical alternatives can be handled more efficiently when responsibilities, information flows, and response procedures are clear and have been proven.

Finally, the findings reinforce the relevance of Perrow's (1984) concepts of interactive complexity and tight coupling, while indicating the limits of applying them directly. DHB1 relationships may become tightly coupled where deviations in electricity supply, production, injection, pressure management, export availability, or control information require coordinated responses. However, the degree of coupling will depend on future technical design, operating procedures, available linepack and storage, market arrangements, control-system configuration, and user flexibility. The analysis therefore does not conclude that DHB1 is inherently a tightly coupled high-risk system; rather, it identifies where tight coupling may develop and where operating margin, coordination, and recovery arrangements are particularly important.

Overall, the findings show that vulnerability in emerging hydrogen infrastructure is relational, developmental, and cross-level. It is relational because it arises through dependencies between assets, actors, and institutions; developmental because it is shaped while infrastructure, market arrangements, regulation, and commitments are still being established; and cross-level because organizational decisions affect physical operation while technical constraints trigger commercial, regulatory, and coordination responses. For DHB1, resilience depends not only on robust pipelines and stations, but also on alignment among technical design, connection responsibilities, market incentives, operational information, regulatory arrangements, and Danish–German coordination.

7.2. Methodological Contribution and Implications

The methodological contribution of this study lies in adapting the Interface Analysis Template (IAT) to examine vulnerability in an emerging hydrogen transport system. The original IAT supports the structured description of interfaces, interaction scenarios, exchanges, functions, requirements, and criticality (Uddin, Campean, & Khan, 2015). In this study, the template was applied to both technical and organizational interfaces and extended through fields C11–C15, which capture dominant interdependency type, interface-specific risk, uncertainty categories, uncertainty level, and vulnerability assessment. This extension made it possible to examine not only how DHB1 interfaces are intended to function, but also how uncertainty and vulnerability may arise around them.

Another methodological contribution is the application of the Extended IAT as the

foundation for building cross-level vulnerability clusters. The additional fields developed for this study make it possible to evaluate each technical and organizational interface not only according to its intended function and requirements, but also in relation to its interdependencies, risk mechanisms, uncertainty, and vulnerability. As a result, structured interface profiles can be developed and compared at both the technical and organizational levels. The cluster-construction process then makes use of these profiles to find interfaces that support the same system function and are linked by plausible pathways of influence. Thus, the approach shifts from individual assessments of interfaces to an analysis of how technical and organizational conditions might interact to cause or increase vulnerability. The methodological contribution is therefore the **combination of an extended interface-level assessment with a systematic clustering process**, which enables the identification of cross-level vulnerability mechanisms without assuming that technical and organizational interfaces are directly comparable.

In contrast to a traditional asset-oriented assessment, this approach showed dependencies that would otherwise remain outside the analysis. For instance, the physical ability to inject hydrogen into DHB1 depends not just on the performance of a producer connection or an I/E station, but also on access to the electricity grid, the delivery from a PtX project, the responsibilities relating to the connection, the permitting process, and the investment decisions of the producer. Likewise, the availability of the southbound export route depends not only on the performance of the Danish pipeline and station, but also on the market arrangements, the capacity commitments, the receiving capacity in Germany, and the cross-border coordination. The method thus enables the tracing of how organizational uncertainty can affect technical operations and how technical constraints can in turn give rise to organizational consequences.

This method could be applied to other emerging infrastructure systems in which physical infrastructure is developed alongside evolving market, regulatory, and institutional arrangements. Nevertheless, the findings still depend on the available documentation, the chosen system boundary, and the qualitative interpretation.

7.3. Practical Implications for DHB1

Chapter 6 identifies four clusters, which show that completing the DHB1 pipeline alone does not make hydrogen transport usable. Its success also relies on commercial commitments, producer readiness, a suitable German export route, and the ability to adapt to changing conditions. The practical implications concern how these dependencies affect the development and use of DHB1.

In Cluster 1, the central issue is whether transport capacity is **commercially attractive and operationally usable**. Producers and shippers face interdependent investment decisions. DHB1 depends on capacity commitments, which partly rely on credible production, off-take, and transport arrangements. Once operating, pressure limits, linepack flexibility, and maintenance needs may constrain the flexibility of booked capacity. Therefore, commercial viability and physical operating margin cannot be assessed independently.

Cluster 2 addresses cross-border export, emphasizing that the practical value of the Danish

corridor is determined by factors extending beyond the Danish system boundary. **The DHB1 route may have limited utility if German receiving or onward-transport capacity is delayed, constrained, or incompatible with Danish delivery conditions**. Restrictions on either side can impact Danish export availability and the operations of shippers and producers. This dependency is particularly significant given that the initial DHB1 configuration offers few physical alternatives for southbound export.

Cluster 3 indicates that readiness depends on **completing and aligning multiple interconnected stages**, rather than a single connection milestone. Electricity access, PtX commissioning, producer connection infrastructure, and compliant delivery at the I/E station must all be synchronized before hydrogen production can serve as usable supply for DHB1. Delays at any stage may result in underutilized capacity elsewhere.

Finally, Cluster 4 demonstrates that DHB1's usable capacity partly depends on operators receiving **accurate and timely system information**. If measurements conflict, data from a station stop reaching the control centre, or a station reports abnormal pressure or flow, Energinet may need to restrict hydrogen transport while investigating. A confirmed issue can affect how much hydrogen producers inject, how much shippers nominate for transport, and how much is delivered across the German border. Operational readiness therefore relies not only on functioning equipment, but also on clear decision-making and communication when measurements or conditions change.

7.4. Mitigation Measures for Cross-Level Vulnerabilities

The results discussed in Chapter 6 suggest that mitigation should address dependencies across technical and organizational interfaces rather than treating individual risks in isolation. A study of interdependent critical infrastructures in Sweden found that cross-sector risk management was shaped by organizational silos, reliance on dedicated individuals and personal relationships, and limited explicit methods for assessing and managing interdependency-related risks. It also identified clear risk ownership as an important factor in cross-sector engagement (Rydén Sonesson, Johansson, & Cedergren, 2021). From a resilience perspective, mitigation should combine measures that prevent avoidable disruption with arrangements for monitoring, responding to, adapting to, and recovering from conditions that cannot be fully predicted (Hickford et al., 2018).

For DHB1, not all uncertainty can be resolved before operation. The relevant task is to make critical dependencies visible, assign responsibility for unresolved issues, and establish decision and review processes that allow technical and organizational arrangements to mature together. Research on infrastructure projects in transition similarly emphasizes shared information, joint procedures, and a system-level perspective when organizations must make interdependent decisions under uncertainty (Røsok, de Bruijne, & Veeneman, 2023).

Several DHB1-specific processes already address aspects of these dependencies, including the capacity sale, staged producer-connection agreements, bundled Danish–German capacity arrangements, and formal cooperation between Energinet and Gasunie Deutschland (Energinet, 2025b, 2026a; Forsyningstilsynet, 2025; Gasunie Deutschland, 2026).

The measures below build on these existing processes by addressing the vulnerability mechanisms identified in Chapter 6.

Market Access, Commercial Viability, and Balancing

The mitigation measures for Cluster 1 aim to manage the project-on-project dependency among hydrogen production, off-take, transport-capacity commitments, and the realization of DHB1. The capacity-sale process and development of market methodologies already provide a basis for addressing this dependency (Energinet, 2024c, 2026a). The remaining challenge is to help prospective users distinguish terms that are established from those that may still change as the market and operating framework develops.

- **Clear booking information:** Maintain clear, accessible information on the conditions relevant to capacity-booking decisions. This includes tariff principles and forecasts, the duration and characteristics of capacity rights, balancing exposure, curtailment conditions, and the status of nomination and re-nomination procedures. For matters still under development, Energinet could identify what remains undecided, the actor or approval process involved, the anticipated next decision stage, and the potential implications for users. This would build on the existing capacity-sale information while helping producers and shippers assess the risks associated with long-term commitments.
- **Review of market assumptions:** Review the assumptions underlying market arrangements at defined stages between capacity booking, commissioning, and early operation. Energinet could compare the expected production and demand profiles, available linepack flexibility, and other operating limits with the assumptions used to develop capacity products and balancing procedures. Where a review identifies a need for change, its implications for future products and for existing agreements should be assessed separately. Any revision affecting regulated methodologies or signed commitments would remain subject to the applicable approval and contractual processes. This applies the resilience principle of adapting arrangements as operating conditions become clearer without treating existing capacity rights as automatically open to revision (Hickford et al., 2018).
- **Testing before operation:** Test how market and operating procedures would work under plausible constraints before commercial operation. Scenarios could include reduced linepack flexibility for balancing, a temporary station restriction, planned pipeline maintenance, or reduced export capacity towards Germany. For each case, the assessment could examine the resulting technical capacity limit, how capacity restrictions would be communicated, how balancing rules would apply to illustrative shipper positions, and when nominations or injections would need to change. The purpose is to identify inconsistencies between expected market flexibility and physical operating limits, so that the relevant procedures can be refined before they are needed in practice.

Danish-German Export Alignment

For Cluster 2, the Danish-German connection should be treated as a shared functional interface rather than as two projects that meet only physically at the border. Existing arrangements already address parts of this dependency. Bundled cross-border capacity arrangements and coordinated capacity processes support market access, while the Joint Development Agreement provides a framework for project-level cooperation (Energinet, 2026a; Forsyningstilsynet, 2025; Gasunie Deutschland, 2026). Energinet also identifies a future Operation Agreement to define day-to-day coordination at the border (Energinet, 2026a). The mitigation priority is to ensure that this agreement addresses how the two operators will respond when conditions on either side restrict cross-border hydrogen transport.

- **Responsibilities and notifications:** Energinet and Gasunie Deutschland should agree on who communicates changes to available capacity or delivery conditions, when the other operator must be notified, and how planned maintenance and unexpected outages are coordinated. The procedures should also specify what each operator does when a restriction requires changes to shipper nominations, balancing actions, curtailment, or restoration of service. Because DHB1 has limited alternative routes for southbound export, a restriction at the border could affect the wider Danish system. Clear responsibilities and communication procedures would help both operators manage that impact consistently and inform affected market participants.
- **Shared interface register:** The existing cooperation framework could be supported by a shared interface register that records cross-border matters requiring decisions or ongoing coordination. It could cover project milestones, available capacity, technical delivery requirements, fiscal metering and hydrogen-quality measurement, maintenance windows, operational restrictions, and restoration procedures. Each entry should identify the responsible party, the relevant decision point, and how changes are communicated to the other operator and affected market participants. This would serve as a working tool within existing cooperation arrangements, rather than a replacement for the agreements themselves.
- **Joint testing before operation:** The agreed procedures should be jointly tested before commercial operation. Scenarios could include delayed German receiving capacity, a temporary downstream restriction, planned maintenance on either side of the border, and conflicting or unavailable measurement information. For each scenario, the operators could assess whether both systems produce consistent decisions on available capacity, notifications, nominations, balancing, curtailment, and restoration. Such testing would help identify gaps in responsibilities or communication before the procedures are needed during an actual restriction (Røsok, de Bruijne, & Veeneman, 2023; Rydén Sonesson, Johansson, & Cedergren, 2021).

Producer Entry and Upstream Integration

For Cluster 3, the suggested mitigation involves utilizing Energinet's connection process to evaluate if the producer's electricity connection, PtX facility, hydrogen pipeline, and DHB1

I/E station will all be operational within compatible timeframes, enabling hydrogen injection as planned. This early connection process, which includes receiving project details, assigning a connection point, and establishing a pre-construction agreement to develop the connection, followed by a connection agreement for construction and operation, provides a basis for assessment (Energinet, 2026a). The goal is to verify whether all parts of the supply chain will be ready to operate together, rather than assuming that completion of one part guarantees hydrogen injection into DHB1.

- **Coordinated readiness review:** During connection maturation, Energinet and each prospective producer could review the expected readiness of the electricity connection, PtX facility, hydrogen-conditioning and compression equipment, producer pipeline, and I/E station. The review should also cover permitting and land rights, metering, hydrogen-quality measurement, data exchange, and procedures for isolation and return to service. It should document unresolved dependencies, the responsible party for each, and the timing for confirming readiness before commissioning. This would reduce the risk that a facility is ready in one part of the chain but cannot deliver hydrogen meeting the requirements for injection into DHB1.
- **Shared connections where suitable:** When producers are geographically close, a shared connection approach can be considered during connection development as an alternative to individual pipelines. Depending on the location and design, shared infrastructure might reduce duplicate routing, land negotiations, permitting efforts, construction costs, and environmental impacts. However, these advantages must be balanced against the need for increased coordination and the risk that restrictions in a shared pipeline could impact multiple producers. This option should be evaluated alongside separate connections, considering technical feasibility, lifecycle costs, timing, reliability, environmental effects, and access and operational requirements.

  If a shared connection is found to be technically and economically suitable, its governance would need to be defined before development proceeds. This includes who finances, owns, and operates the pipeline; how producers obtain access and capacity; who is responsible for metering and data exchange; and how service is restored after a disruption. A shared pipeline may reduce the need for separate connections, but it also creates a common asset on which several producers depend. The appropriate ownership and operating model should therefore be assessed alongside the technical design.
- **Interruption and restart procedures:** Once a producer is connected, the arrangements must also account for changes in hydrogen delivery caused by electricity interruptions. An abrupt interruption may reduce PtX output and alter injection at the I/E station, while a prolonged electricity restriction may require further production reductions. Producer connection and operating procedures should specify how changes in expected hydrogen delivery are communicated, when injection must be reduced or stopped, and what conditions must be met before injection resumes. These hydrogen-side procedures should take into account each producer's electricity-connection terms; they should not be assumed to determine electricity-grid curtailment priorities. Any implications of limited-grid-access products should be assessed against the producer's actual agreement, rather than assumed to apply uniformly (Energinet, 2024a).

- **Metering and injection authority:** Before commissioning, the producer and Energinet should confirm their respective responsibilities for fiscal metering, hydrogen-quality measurement, data access, and decisions to accept or suspend injection at the I/E station. These responsibilities matter for settlement and quality compliance as well as for determining whether hydrogen can enter DHB1.

Operational Information, Control, and Coordination

For Cluster 4, the mitigation priority is to ensure that information from DHB1 stations and producer connections supports consistent operational decisions across organizational boundaries. Energinet's project documentation already identifies measurement and validation at I/E stations, operational data exchange with connected users, and SCADA as parts of the planned system (Energinet, 2025a, 2025c). The recommendation is therefore not to introduce these functions, but to verify how the information they provide is interpreted and acted on when operating conditions are abnormal. Before commercial operation, Energinet and connected producers should establish **how uncertain measurements lead to an operating decision**: how they will respond when a critical measurement is missing, conflicts with another reading, or indicates that hydrogen may not meet the conditions for injection. The relevant procedures should specify who checks the information, who decides whether injection at the affected connection can continue, how that decision is communicated, and what must be confirmed before normal injection resumes. This addresses the cross-level vulnerability identified in Cluster 4: an uncertain technical condition can reduce usable capacity or delay restoration when the organizations involved do not have a shared basis for making and communicating the operating decision.

Overall Mitigation Approach

Taken together, the four clusters point to three mitigation principles:

- **Responsibility for unresolved dependencies:** Dependencies should be identified, assigned to responsible actors, and revisited at relevant decision points.
- **Coordination at shared interfaces:** Arrangements should specify how the parties coordinate their decisions without duplicating existing regulatory or contractual responsibilities.
- **Agreed response and restoration:** Where a disruption involves more than one actor, the parties should establish how information is interpreted, decisions are communicated, and service is restored.

The measures apply at different stages of DHB1's development. Transparency about unresolved commercial dependencies is particularly important before capacity commitments and investment decisions. Producer readiness and cross-border coordination should be addressed as connection and operating arrangements are developed. Before commercial operation, the parties should confirm how they will respond to uncertain measurements and

test the proposed response to relevant cross-border restrictions. These arrangements can then be reviewed as experience from commissioning and operation becomes available.

The aim is not to eliminate all vulnerability from DHB1. It is to reduce the risk that uncertainty or disruption at one interface causes avoidable effects elsewhere in the system, while allowing the arrangements to be refined as more becomes known during construction, commissioning, and operation.

7.5. Limitations and Research Quality

This study's findings should be considered in the context of DHB1's development stage, the available evidence, and the qualitative approach used. This section outlines how these factors limit the conclusions that can be drawn and explains how the study addressed them where possible.

A first limitation concerns the timing of the research. DHB1's infrastructure, market framework, producer connections, and cross-border arrangements were still evolving during the study; therefore, some conditions identified in the analysis may change over time. For this reason, the analysis focuses on vulnerability mechanisms: how dependencies and uncertainties across technical and organizational interfaces can create vulnerabilities that propagate between these two levels. Illustrative scenarios show how these mechanisms might arise in practice, rather than aiming to predict specific failure situations in DHB1's future operations. Although the scenarios may change as DHB1 develops, the underlying mechanisms will likely remain relevant where similar dependencies persist. This distinction allows the findings to inform later assessments of DHB1 and the examination of comparable interfaces in other emerging hydrogen infrastructure projects.

A second limitation relates to the evidence based on documents. The analysis used publicly accessible project materials, especially Energinet's documentation on the Danish configuration, producer connections, and market arrangements. This documentation was also updated over the research period as new information about DHB1 emerged. The findings reflect the DHB1 plans and arrangements as described in the documents available during this research. If those plans or arrangements change, some specific conclusions might need revision. To make the documentary basis of the analysis transparent, the references identify the sources used and provide their publication and access dates where available.

Additionally, some relevant information was not publicly available, including internal project decisions, producer contracts, and detailed cross-border operating arrangements. When a process or agreement was not described in public documentation, the study did not assume that it did not exist. Instead, it distinguished conclusions supported by documented information from inferences about possible consequences. Nevertheless, the study could not assess arrangements that were not publicly available, and this could have an impact on how the identified vulnerabilities were interpreted.

Stakeholder representation is another limitation. The four interviews helped refine the initial clusters but did not encompass all categories. There were no interviews with

Gasunie Deutschland, which is the German transmission and system operator, prospective shippers or off-takers, distribution network operators, public authorities, landowners, or local communities. Additionally, a single PtX expert cannot represent all prospective producers. The interviews were mainly used to challenge document-based interpretations rather than to establish stakeholder consensus or validate each interface assessment.

A limitation regarding the methodological framework is that the Extended Interface Analysis Template requires analytical judgment. Decisions about which interfaces to include, which interdependency is dominant, and how to rate uncertainty and vulnerability depend on the system boundary, the available evidence, and the study's qualitative criteria. The ratings were informed by underlying documentary sources used to assess each interface; they were not assigned without an evidential basis. Interface descriptions were developed from documented functions and requirements, and the cluster-construction criteria required technical and organizational interfaces to support a shared function and a plausible cross-level pathway. Preliminary mechanisms were also compared with expert feedback. These steps make the reasoning behind the assessments more transparent, but they do not turn the 0–2 ratings into measured probabilities or objective safety rankings. The four clusters should therefore be read as selected plausible vulnerability pathways, not an exhaustive account of DHB1's dependencies or a ranking of the most likely failures.

The system boundary further limits the conclusions. The analysis considers evidence about German infrastructure where it is relevant to DHB1's export function and could affect the Danish system, but it does not identify and assess the interfaces throughout the German hydrogen network. Including them could provide a deeper understanding of vulnerabilities across the Danish-German corridor. Similarly, the study considered PtX plants, electricity connections, and producer pipelines where they affect hydrogen entry, but it did not assess each project's design. Without hydraulic modeling, detailed, probabilistic risk analysis, or economic evaluation, the study can identify plausible pathways of impact but cannot quantify their likelihood, duration, financial effects, or precise hydraulic consequences.

A final limitation is that the analytical approach was only tested on DHB1. The study expands the Interface Analysis Template to evaluate interdependencies, risks, and uncertainties in both technical and organizational interfaces, employing a clustering process to find cross-level vulnerability mechanisms. Its use with DHB1 demonstrates how this method can support developing hydrogen infrastructure projects, but it remains uncertain whether it would identify similar vulnerabilities in other projects or different contexts. Additional applications are necessary to determine its wider application.

8

Conclusions and Future Research Recommendations

This thesis investigated the emergence of vulnerabilities within and across the technical and organizational levels of hydrogen transport infrastructure under conditions of socio-technical integration and uncertainty. The Danish Hydrogen Backbone 1 (DHB1) served as a pre-operational case study, where planned physical infrastructure, producer projects, market arrangements, regulation, and cross-border coordination are developing concurrently. The analysis integrated documentary evidence, an Extended Interface Analysis Template (IAT), cross-level cluster analysis, and expert review of preliminary cluster interpretations. The findings address vulnerability mechanisms, supported with illustrative scenarios that could arise from these vulnerabilities taking place in the context of the Danish hydrogen transport network.

8.1. Conclusions and Answers to the Research Questions

To address the first sub-question, "What are the relevant technical components, organizational actors, and system boundaries of the DHB1 case?", the study defined the system boundary around the conditions necessary for hydrogen to enter DHB1, move through the Danish transmission corridor, and be delivered to Germany. This corridor includes the new Bramming–Veerst pipeline, the existing pipeline planned for conversion between Veerst and Frøslev, mainline stations, line-valve stations, potential injection/extraction (I/E) stations, and measurement, protection, and control systems. Relevant actors include Energinet, prospective producers and shippers, the Danish Utility Regulator, and Gasunie Deutschland. The broader stakeholder mapping also encompasses public authorities, distribution-network operators, and local stakeholders, although not all actors identified were selected for detailed interface assessment. Electricity supply, PtX production, and producer connections were included where they affect hydrogen entry, as well as German infrastructure affecting Danish exports.

The second sub-question asked which technical and organizational interfaces are relevant to DHB1, along with their functions and interdependencies. The Extended Interface Analysis

Template (IAT) identified ten technical interfaces and five organizational interfaces. The technical interfaces cover electricity supply, hydrogen delivery from producers, I/E-station entry, pipeline transport, pressure regulation, metering, and operational data exchange. The organizational interfaces cover Energinet's relationships with shippers, producers, Gasunie Deutschland, the Danish Utility Regulator, and PtX developers or operators. These interfaces reveal that DHB1's operations depend on physical conditions such as electricity availability, hydrogen quality, pressure, and flow; on information and control systems; and on agreements, capacity rights, balancing mechanisms, and regulations. Overall, physical, cyber, and logical interdependencies therefore intersect at specific interfaces rather than operating as separate layers.

To answer the third sub-question, "What risks and vulnerabilities can be identified at these interfaces?", the study examined the potential consequences of restrictions, alternatives, and protection measures at each chosen interface. The results show different patterns. For the initial southbound export corridor, the pressure change at MRS Veerst and the handling of hydrogen at Padborg MMS are significant because a sustained restriction could limit further transport, and no immediate alternative export route is identified within the assessed configuration. At producer-entry interfaces, vulnerability concerns the alignment of electricity access, PtX production, hydrogen conditioning, infrastructure on the producer side, I/E-station functions, and entry requirements. At organizational interfaces, factors such as capacity commitments, connection responsibilities, evolving market and regulatory frameworks, and Danish-German cooperation influence whether the planned transport capacity will be available and functional.

The fourth sub-question asked, "How do uncertainty and interactions between technical and organizational interfaces contribute to cross-level vulnerability mechanisms?" The analysis shows that uncertainty becomes consequential when actors must make interdependent decisions before the conditions needed to carry them out are fully defined or confirmed. For example, capacity commitments depend partly on developing market arrangements and expected hydrogen flows, while the usefulness of the Danish export corridor depends on compatible infrastructure and operating arrangements on both sides of the border. Chapter 6 identified four pathways through which such dependencies may create vulnerability: market access, tariffs, and balancing in relation to the backbone's physical operating margin; Danish–German coordination in relation to export availability; electricity access and producer connections in relation to hydrogen entry; and operational information and control in relation to coordinated responses to deviations. In each pathway, organizational conditions may affect whether technical capacity is available or usable, while a technical constraint may require commercial, operational, regulatory, or cross-border decisions. Uncertainty can make these interactions harder to anticipate or manage, especially where responsibilities, information, or response procedures have not yet been finalized.

Finally, the fifth sub-question asks, "Which measures could address the identified vulnerabilities and cross-level mechanisms?" The analysis suggests that mitigation should focus on dependencies across interfaces, rather than just individual assets or agreements. Chapter 7 recommends clearer communication of current and unresolved capacity and market conditions; coordinated Danish-German procedures for restrictions, maintenance, and restoration; readiness checks across electricity connections, PtX facilities, producer pipelines,

and I/E stations; and processes for validating and resolving missing or conflicting operational information. These measures build on existing connection, market, regulatory, and cross-border processes, not replace them. Their goal is to clarify information, responsibility, timing, and response to prevent dependencies from becoming operational constraints. Their effectiveness should be evaluated as DHB1 is completed and enters service.

8.2. Future Research

A first direction is to apply the Extended IAT and cross-level clustering approach to other emerging hydrogen transport projects. Comparing cases with different market arrangements, network configurations, storage options, and degrees of physical redundancy would help establish which mechanisms are specific to DHB1 and which recur elsewhere. It would also test whether the assessment criteria and cluster-construction process remain useful beyond this single case.

A second direction is to examine interfaces beyond the present study boundary in greater detail. The German receiving and onward-transport system could be assessed as a connected case rather than only insofar as it affects Danish exports. Project-specific research on PtX plants, electricity-grid connections, producer pipelines, and potential shared connections could clarify how design choices, ownership, permitting, and operating strategies alter the entry-related mechanisms identified here. Broader interviews with German network representatives, shippers, off-takers, producers, public authorities, and communities could challenge or complement the present interpretations.

Finally, future research could assess the long-term economic viability of renewable hydrogen supply chains and its implications for corridors such as DHB1. This would involve comparing the full cost of producing and delivering hydrogen with off-takers' willingness to pay, considering electricity costs, electrolyzer utilization, connection costs, transport tariffs, financing, and policy support. Comparing market and policy scenarios could clarify the conditions under which supply becomes commercially viable. This would complement the present study, which identifies dependencies between commercial commitments and infrastructure development but does not quantify the costs and revenues needed to sustain production and transport.

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A

Extended Interface Analysis Template

A.1. Technical Interfaces

Table A.1: Completed IAT: Technical Interfaces.

Field	Assessment
T1: Bramming PLR – New Bramming–Veerst pipeline	
C1: Interface ID	T1
C3: Interaction scenario	Hydrogen is transferred between the Bramming PLR/main valve station and the new Bramming–Veerst hydrogen pipeline during commissioning, normal pipeline operation, pigging, maintenance, start-up, shutdown, and incident-response activities. The interface enables safe continuation or controlled isolation of hydrogen flow at the upstream end of the new pipeline section, while supporting the establishment and
C3: Interaction scenario (cont.)	maintenance of the applicable pressure and linepack conditions.
C4: Exchange type	Material (M) Physical (P)
C5: Interaction function	Safely transfer, isolate, and control hydrogen at the upstream end of the new Bramming–Veerst pipeline, enabling pipeline commissioning, pigging, maintenance, start-up, shutdown, and normal southbound transport while maintaining compatible pressure, flow, hydrogen-quality, temperature, and linepack conditions.
C6: From	Bramming PLR / main valve station (PLR Bramming). Including pig launcher/receiver, main isolation valve and vent stack.
C7: To	New 36-inch Bramming–Veerst hydrogen pipeline.
C8: Requirements	Keep pressure and linepack within the new section's 50–90 barg operating range and maximum 30-bar pressure variation; final daily limits remain to be set. Meet preliminary hydrogen limits: H_2 at least 99.5 mol-%, inerts at most 0.5 mol-%, water at most 20 ppm, temperature 0–45 °C. Provide isolation, venting, overpressure protection, monitoring, alarms, and control.
C9: Criticality	+2
C10: High-level function	Enable safe and continuous entry of hydrogen into the new Bramming–Veerst pipeline, supporting the build-up and maintenance of southbound flow, linepack, and export capability in DHB1.
C11: Interdependency	Physical interdependency: Pressure, flow, temperature, and hydrogen-quality conditions at the Bramming PLR/main valve station directly determine the hydraulic state and gas composition of the connected Bramming–Veerst pipeline section.
C12: Principal risks	Failure or incorrect operation of the Bramming valve, PLR, venting, instruments, or protection may restrict transfer or delay isolation. Incorrect isolation, venting, startup, shutdown, or pigging can cause pressure and flow transients, reduce linepack, or trap hydrogen. Leakage or unintended pressurization may cause a local release; off-limit pressure, flow, quality, or temperature may require restriction. Missing
C12: Principal risks (cont.)	or inaccurate monitoring may delay response. Final controls and failure scenarios depend on detailed design and safety studies.
C13: Uncertainty categories	Technology-performance uncertainty.
C14: Uncertainty level	3
C15: Vulnerability assessment	5

Technical Interfaces (continued)

Field	Assessment
T2: DHB1 mainline – line-valve stations	
C1: Interface ID	T2
C3: Interaction scenario	Hydrogen flows through the DHB1 mainline past line-valve (LV) stations located along both the new Bramming–Veerst pipeline and the converted Veerst–Frøslev pipeline. At each LV station, mainline valves and vent stacks can be operated to isolate and depressurise pipeline sections for planned maintenance or in response to an incident, while maintaining safe operating conditions in the remaining parts of DHB1.
C4: Exchange type	Material (M) Physical (P)
C5: Interaction function	Safely transport hydrogen through the DHB1 mainline while enabling controlled isolation, sectionalizing, venting, and depressurization of pipeline sections at line-valve stations for maintenance and incident management.
C6: From	Upstream DHB1 pipeline segment, carrying pressurised hydrogen toward the line-valve station.
C7: To	Line-valve station mainline valve, isolation, and venting equipment, connected to the downstream DHB1 pipeline segment.
C8: Requirements	Keep pressure and flow within the new (50–90 barg) or converted (35–58 barg) section limits and control pressure gradients during isolation and venting. Meet preliminary hydrogen quality and temperature limits (H_2 at least 99.5 mol-%, inerts at most 0.5 mol-%, water at most 20 ppm, 0–45 °C); final daily limits remain to be set.
C9: Criticality	+2
C10: High-level function	Enable safe isolation, sectionalizing, and depressurization of DHB1 pipeline sections for maintenance and incident management, while maintaining pressure, flow, linepack, and hydrogen-quality conditions in the remaining available export corridor.
C11: Interdependency	Physical interdependency: Valve status, isolation, and venting operations at each LV station directly affect the pressure, flow, and linepack of the connected DHB1 pipeline sections.
C12: Principal risks	A line valve failing to open or close may delay isolation and extend curtailment. Rapid depressurization or incorrect valve sequencing can cause pressure transients, imbalance, stranded linepack, or unintended interruption. Leakage from valves, actuators, or vent stacks can cause a local hydrogen release.
C13: Uncertainty categories	Technology-performance uncertainty.
C14: Uncertainty level	2
C15: Vulnerability assessment	2

Technical Interfaces (continued)

Field	Assessment
T3: DHB1 mainline – injection/extraction (I/E) stations	
C1: Interface ID	T3
C3: Interaction scenario	Hydrogen is injected into or withdrawn from the DHB1 mainline through future injection/extraction (I/E) stations. I/E stations may be constructed at any of the nine planned DHB1 station locations, including Bramming, Veerst, Padborg, and line-valve-station locations subject to concluded connection agreements with producers, consumers, or other eligible users. The interface enables controlled hydrogen entry or exit
C3: Interaction scenario (cont.)	while maintaining the operating conditions of the relevant DHB1 pipeline section.
C4: Exchange type	Material (M) Physical (P). Information (I)
C5: Interaction function	Safely inject hydrogen into, or withdraw hydrogen from, the DHB1 mainline through I/E stations while validating flow and hydrogen quality, maintaining compatible pressure, temperature, and flow conditions, and enabling monitoring, control, cut-off, and incident response.
C6: From	DHB1 mainline at the relevant I/E-station connection points.
C7: To	DHB1 injection/extraction stations
C8: Requirements	Keep injection and withdrawal within connection-specific pressure, flow, capacity, ramp-rate, and linepack limits; the new and converted sections operate at 50–90 and 35–58 barg. Injection must meet preliminary hydrogen quality and temperature limits (H_2 at least 99.5 mol-%, inerts at most 0.5 mol-%, water at most 20 ppm, 0–45 °C). Energinet validates flow and quality; agreements specify data, alarms,
C8: Requirements (cont.)	isolation, cutoff, and off-specification response.
C9: Criticality	+2
C10: High-level function	Enable safe, compliant, and controllable producer entry and consumer offtake at DHB1 I/E stations while maintaining pressure, flow, linepack, hydrogen-quality, and operational-security conditions in the connected backbone section.
C11: Interdependency	Physical interdependency, with secondary cyber and logical dependencies. Injection or withdrawal directly affects pressure, flow, linepack, and hydrogen quality in the connected pipeline section. Reliable metering, quality data, alarms, and control signals are required for monitoring and response, while connection agreements allocate technical limits, responsibilities, data exchange, and incident procedures.
C12: Principal risks	Injection or withdrawal beyond pressure, flow, ramp-rate, or capacity limits may reduce linepack or require curtailment. Off-specification hydrogen may require rejection or isolation. Faulty or delayed measurement, validation, alarms, or data exchange may delay response; unclear cutoff and incident responsibilities can compound this. The effect of changes in producer or consumer activity depends on connection
C12: Principal risks (cont.)	limits, buffering, and control.
C13: Uncertainty categories	Infrastructure and project-delivery uncertainty; demand and market uncertainty; technology-performance uncertainty.
C14: Uncertainty level	5
C15: Vulnerability assessment	3

Technical Interfaces (continued)

Field	Assessment
T4: New Bramming–Veerst pipeline – Mainline Regulator Station (MRS) Veerst.	
C1: Interface ID	T4
C3: Interaction scenario	Hydrogen from the upstream Bramming–Veerst hydrogen pipeline flows into MRS Veerst, where its pressure and flow are regulated before the gas enters the downstream repurposed pipeline toward Germany.
C4: Exchange type	Material (M) Physical (P)
C5: Interaction function	Safely convey hydrogen from the new Bramming–Veerst pipeline into MRS Veerst while maintaining inlet pressure, flow, temperature, and hydrogen quality conditions compatible with controlled regulation and onward transport.
C6: From	New 36-inch Bramming–Veerst hydrogen pipeline
C7: To	Mainline Regulator Station (MRS) Veerst
C8: Requirements	Maintain inlet pressure and flow compatible with the new section's 50–90 barg range and MRS Veerst regulation. Meet preliminary hydrogen quality and temperature limits (H_2 at least 99.5 mol-%, inerts at most 0.5 mol-%, water at most 20 ppm, 0–45 °C). Provide control, isolation, venting, and overpressure protection; final settings depend on detailed design.
C9: Criticality	+2
C10: High-level function	Enable safe transfer of hydrogen from the new Bramming–Veerst pipeline into MRS Veerst, providing the inlet conditions required for pressure regulation and continued southbound transport through DHB1.
C11: Interdependency	Physical interdependency: Inlet pressure, flow, temperature, and hydrogen quality from the new Bramming–Veerst pipeline directly determine the operating condition of MRS Veerst and its ability to safely regulate hydrogen for onward transport.
C12: Principal risks	Inlet pressure or flow outside MRS limits may reduce regulation or capacity, trigger protection, or require curtailment. Valve, instrument, isolation, or protection failure may restrict transfer; off-specification quality or temperature may require isolation. Startup, shutdown, pigging, and upstream changes can create transients whose impact depends on control settings and operating margin.
C13: Uncertainty categories	Technology-performance uncertainty.
C14: Uncertainty level	3
C15: Vulnerability assessment	5

Technical Interfaces (continued)

Field	Assessment
T5: MRS Veerst – converted Danish pipeline section	
C1: Interface ID	T5
C3: Interaction scenario	Hydrogen leaves Mainline Regulator Station (MRS) Veerst after pressure reduction and flow regulation and enters the converted Danish pipeline section for continued southbound transport toward Padborg, Frøslev, and the Danish–German interconnection. The interface transfers hydrogen from the operating conditions of the MRS outlet into the lower-pressure converted pipeline while maintaining safe pressure, flow,
C3: Interaction scenario (cont.)	hydrogen-quality, temperature, and linepack conditions.
C4: Exchange type	Material (M) Physical (P)
C5: Interaction function	Safely transfer hydrogen with the adequate pressure from MRS Veerst into the converted Danish pipeline section while maintaining outlet conditions compatible with the converted pipeline's operating limits and onward export function.
C6: From	MRS Veerst outlet equipment
C7: To	Converted Danish hydrogen pipeline section from Veerst toward Frøslev/Padborg and the Ellund interconnection.
C8: Requirements	Keep MRS outlet pressure and flow within the converted pipeline's 35–58 barg range and maximum 10-bar pressure variation. Meet preliminary hydrogen quality and temperature limits (H_2 at least 99.5 mol-%, inerts at most 0.5 mol-%, water at most 20 ppm, 0–45 °C). Provide regulation, isolation, venting, monitoring, alarms, and overpressure protection; final settings remain to be defined.
C9: Criticality	+2
C10: High-level function	Enable safe onward transfer of hydrogen from MRS Veerst into the converted Danish pipeline section, maintaining the pressure, flow, quality, temperature, and linepack conditions required for southbound transport toward the Danish–German interconnection.
C11: Interdependency	Physical interdependency: MRS outlet pressure, flow, temperature, and hydrogen quality directly determine the hydraulic state and gas composition of the connected converted pipeline section.
C12: Principal risks	Excess outlet pressure or faulty reduction may trigger protection, curtailment, or integrity concerns; insufficient pressure or flow limits southbound capacity. Control, isolation, venting, or protection failures can restrict transfer, while off-specification hydrogen may require isolation. Startup, shutdown, pigging, and supply changes can create transients; effects depend on final settings, procedures, and
C12: Principal risks (cont.)	linepack margin.
C13: Uncertainty categories	Technology-performance uncertainty.
C14: Uncertainty level	4
C15: Vulnerability assessment	5

Technical Interfaces (continued)

Field	Assessment
T6: DHB1 I/E station – Energinet SCADA	
C1: Interface ID	T6
C3: Interaction scenario	Operational measurements, status signals, alarms, and control commands are exchanged between DHB1 injection/extraction (I/E) stations and Energinet's central control and SCADA system. The interface enables supervision of pressure, flow, hydrogen-quality status, valve position, and relevant alarms at future I/E stations, as well as authorized control actions required for safe injection, withdrawal, cut-off, and
C3: Interaction scenario (cont.)	incident response.
C4: Exchange type	I (Information)
C5: Interaction function	Provide Energinet's control system with timely and reliable I/E-station data on pressure, flow, hydrogen quality, valve status, alarms, and operating condition, while transmitting authorized control commands and set-points to support safe supervision, cut-off, isolation, and operation of injection and withdrawal functions.
C6: From	DHB1 I/E-station instrumentation and local control equipment.
C7: To	Energinet central control and SCADA system for DHB1
C8: Requirements	Supply accurate, timely I/E-station flow, quality, pressure, temperature, valve-status, and alarm data. Support secure data exchange, authorized commands, event logging, and confirmation of isolation and cutoff. Local protection must remain effective if SCADA is unavailable; final signals and protocols depend on design and agreements.
C9: Criticality	+2
C10: High-level function	Ensure safe, efficient, and coordinated supervision and control of hydrogen injection and withdrawal at DHB1 I/E stations through reliable operational data, quality information, alarm handling, and authorized control capability.
C11: Interdependency	Cyber interdependency. Central supervision and authorized control of I/E-station operation depend on the availability, integrity, timeliness, and accuracy of data and communication between I/E stations and Energinet's control system.
C12: Principal risks	Lost or degraded telemetry, quality data, communication, or remote control reduces visibility and may require local operation or precautionary cutoff. Missing or conflicting readings can delay diagnosis or lead to inappropriate decisions. Unauthorized access, manipulated commands, or denial of service can impair control; mismatched alarms, interlocks, or set points may produce conflicting responses.
C13: Uncertainty categories	Technology-performance uncertainty.
C14: Uncertainty level	1
C15: Vulnerability assessment	2

Technical Interfaces (continued)

Field	Assessment
T7: PtX plant / hydrogen production system – producer connection pipeline	
C1: Interface ID	T7
C3: Interaction scenario	Hydrogen produced by the PtX plant is compressed, dried, conditioned, monitored, and transferred from the production system into the producer service line or dedicated connection pipeline leading toward the DHB1 I/E station. The interface establishes the producer-side hydrogen delivery profile before any buffering, pressure management, measurement, quality validation, and final injection arrangements at the
C3: Interaction scenario (cont.)	downstream I/E station.
C4: Exchange type	Material (M) Physical (P)
C5: Interaction function	Safely transfer conditioned hydrogen from the PtX production system into the producer service line/connection pipeline while maintaining compatible hydrogen quality, temperature, pressure, flow, and monitoring conditions for onward delivery to the DHB1 I/E station.
C6: From	PtX plant / hydrogen production system (electrolyzers, compression and gas conditioning)
C7: To	Producer connection pipeline to DHB1 (dedicated export pipeline segment upstream of IE station)
C8: Requirements	Deliver conditioned, unodorized hydrogen meeting preliminary limits (H_2 at least 99.5 mol-%, inerts at most 0.5 mol-%, water at most 20 ppm, 0–45 °C) and connection-specific pressure, flow, and ramp-rate limits. Monitor flow, quality, pressure, equipment, and alarms; define isolation, notification, and data exchange. Delivery flexibility depends on compression, storage, operating strategy, and linepack.
C9: Criticality	+2
C10: High-level function	Enable safe, compliant, and controllable transfer of hydrogen from PtX production into the producer connection infrastructure for onward delivery to DHB1.
C11: Interdependency	Physical interdependency. Hydrogen quality, pressure, temperature, and flow at the PtX outlet directly determine conditions in the producer service line/connection pipeline.
C12: Principal risks	Off-specification hydrogen may breach quality requirements or compromise connection-pipeline integrity. Compressor trips, unstable production, or rapid ramping can cause pressure and flow transients. Poor monitoring may delay detection, while unclear shutdown, isolation, notification, and data-sharing responsibilities can delay a coordinated response.
C13: Uncertainty categories	Technology-performance uncertainty; supply and resource uncertainty.
C14: Uncertainty level	5
C15: Vulnerability assessment	4

Technical Interfaces (continued)

Field	Assessment
T8: Electricity transmission grid – PtX plant / electrolyzers	
C1: Interface ID	T8
C3: Interaction scenario	Electrical energy is supplied from the transmission grid, through the relevant grid connection, substation, transformers, switchgear, and cabling, to the PtX plant's electrolyzer and auxiliary systems. The available electricity capacity, availability, power quality, and curtailment conditions shape the PtX plant's ability to produce hydrogen and its possible operating profile.
C4: Exchange type	Energy (E)
C5: Interaction function	Supply electrical energy to operate electrolyzers and associated PtX equipment within the agreed grid-connection and power-quality conditions, enabling hydrogen production for potential onward delivery to the producer connection pipeline and DHB1.
C6: From	Electricity transmission grid (high-voltage substations, transformers and protection systems)
C7: To	PtX plant electrical connection and electrolysis systems (electrolyzers, auxiliaries and plant electrical switchgear)
C8: Requirements	Meet grid-code and connection-agreement requirements for voltage, frequency, harmonics, fault level, capacity, and operating limits. Specify commissioning and curtailment conditions. Coordinate protection, disconnection, and restart, and exchange metering, status, outage, and curtailment information.
C9: Criticality	+2
C10: High-level function	Enable reliable and controllable supply of electrical energy from the transmission grid to PtX electrolyzers, so that hydrogen production for DHB1 can operate as planned within system and market constraints.
C11: Interdependency	Physical interdependency, with secondary cyber and logical dependencies. The PtX plant physically depends on electricity supplied by the transmission grid; monitoring, protection, and control systems create cyber dependencies; grid-connection agreements, capacity rights, curtailment conditions, and grid codes create logical dependencies.
C12: Principal risks	Outages, connection failures, grid congestion, or curtailment may reduce electricity supply and PtX output; effects on DHB1 depend on storage, linepack, plant flexibility, and other producers. Power-quality disturbances may trip or damage equipment. Poor protection, communication, or restart coordination can prolong interruption or lead to unsafe reconnection.
C13: Uncertainty categories	Supply and resource uncertainty; technology-performance uncertainty; infrastructure and project-delivery uncertainty.
C14: Uncertainty level	5
C15: Vulnerability assessment	3

Technical Interfaces (continued)

Field	Assessment
T9: Producer service line / connection pipeline – DHB1 I/E station	
C1: Interface ID	T9
C3: Interaction scenario	Hydrogen is transferred from the producer owned or third-party operated service line/connection pipeline into the DHB1 I/E station. At the station, Energinet measures and validates hydrogen flow and quality and provides the regulation, isolation, and safety functions necessary for injection into the DHB1 transmission pipeline.
C4: Exchange type	Material (M) Physical (P)
C5: Interaction function	Transfer hydrogen from the producer connection facility into the DHB1 I/E station under conditions that allow Energinet to validate the gas and safely regulate, isolate, and inject it into the transmission system.
C6: From	Producer service line / connection pipeline.
C7: To	DHB1 I/E station owned and operated by Energinet.
C8: Requirements	Deliver unodorized hydrogen within preliminary quality and temperature limits (H_2 at least 99.5 mol-%, water at most 20 ppm, 0–45 °C, with other contaminant limits) and agreed pressure, flow, ramp-rate, and capacity limits. Energinet validates flow and quality. Final agreements define data, alarms, cutoff, restoration, physical handover, access, maintenance, isolation, and emergency responsibilities.
C9: Criticality	+2
C10: High-level function	Enable safe, compliant, metered, and controllable injection of hydrogen from a direct producer into DHB1.
C11: Interdependency	Physical interdependency, with secondary cyber and logical dependencies. The quality, pressure, temperature, and flow of hydrogen from the service line directly affect the I/E station and DHB1 operating conditions. Metering, validation, data exchange, alarms, and control create secondary cyber dependencies; the connection agreement, ownership boundary, operating responsibilities, and capacity arrangements create
C11: Interdependency (cont.)	secondary logical dependencies.
C12: Principal risks	Off-specification hydrogen may require rejection or isolation and, if undetected, affect integrity or downstream use. Pressure, flow, or ramp-rate deviations may exceed station or mainline limits. Faulty metering, validation, telemetry, or alarms can delay response and create settlement or responsibility disputes. Valve or isolation failures can interrupt injection; unclear handover, maintenance, emergency, or
C12: Principal risks (cont.)	restart roles can prolong disruption.
C13: Uncertainty categories	Infrastructure and project-delivery uncertainty; policy and regulatory uncertainty; technology-performance uncertainty.
C14: Uncertainty level	5
C15: Vulnerability assessment	4

Technical Interfaces (continued)

Field	Assessment
T10: Converted Danish pipeline section – Padborg Mainline Metering Station.	
C1: Interface ID	T10
C3: Interaction scenario	Hydrogen flows southbound from the repurposed Veerst–Frøslev Danish pipeline section into the Padborg Mainline Metering Station (MMS). Padborg MMS receives the hydrogen at the upstream station inlet and regulates pressure and flow, measures hydrogen flow and quality, and provides protection and isolation functions before onward delivery to the Danish–German interconnection.
C4: Exchange type	Material (M) Physical (P)
C5: Interaction function	Transfer hydrogen safely from the repurposed Danish pipeline into Padborg MMS, providing stable inlet conditions for station-based pressure/flow regulation, flow and quality measurement, protection, and onward cross-border export.
C6: From	Repurposed Veerst–Frøslev Danish hydrogen pipeline section.
C7: To	Padborg Mainline Metering Station (MMS)
C8: Requirements	Keep inlet pressure and flow within the converted pipeline's 35–58 barg range, maximum 10-bar pressure variation, and station limits. Meet preliminary quality and temperature requirements (H_2 at least 99.5 mol-%, water at most 20 ppm, 0–45 °C, plus applicable contaminant limits). Provide metering, regulation, isolation, venting, and overpressure protection; coordinate maintenance and restoration with upstream
C8: Requirements (cont.)	and border systems.
C9: Criticality	+2
C10: High-level function	Enable safe and stable delivery of hydrogen from the repurposed Danish pipeline into Padborg MMS for measurement, pressure/flow control, and onward export to Germany.
C11: Interdependency	Physical interdependency, with secondary cyber dependency. The pressure, flow, linepack, and gas-quality conditions in the repurposed pipeline directly determine the operating conditions at the Padborg MMS inlet. Station sensors, alarms, and control systems provide secondary cyber support for monitoring and managing these conditions.
C12: Principal risks	Upstream pressure or flow deviations, linepack changes, or uncoordinated startup and shutdown may exceed MMS inlet limits or restrict export. Off-specification hydrogen may require isolation. Failed valves, regulation, sensors, venting, or overpressure protection can prevent safe receipt and control; poor maintenance or restoration coordination can prolong curtailment.
C13: Uncertainty categories	Technology-performance uncertainty.
C14: Uncertainty level	4
C15: Vulnerability assessment	5

Sources for the technical interfaces assessments: (American Society of Mechanical Engineers, 2023; Energinet, 2024d, 2025b, 2025c, 2025d; European Committee for Standardization, 2023; European Industrial Gases Association, 2023; Uddin, Campean, & Khan, 2015).

A.2. Organizational Interfaces

Table A.2: Completed IAT: Organizational Interfaces.

Field	Assessment
O1: Energinet (HTNO / DHB1 owner) – Shippers (Network Users)	
C1: Interface ID	O1
C3: Interaction scenario	Energinet provides regulated access to DHB1 for shippers through capacity-sale arrangements. Shippers obtain capacity rights for relevant entry and exit points and, once DHB1 is operational, are expected to nominate and, where permitted, re-nominate intended flows and to manage their balancing responsibilities. Energinet provides the applicable market information, system information, and operational arrangements
C3: Interaction scenario (cont.)	needed for shippers to use DHB1 within the developing entry–exit framework.
C4: Exchange type	I (Information)
C5: Interaction function	Provide shippers with transparent access to DHB1 capacity and the information and procedures required to use booked capacity, communicate expected flows, maintain balance, and respond to operational restrictions or balancing actions.
C6: From	Energinet as Hydrogen Transmission Network Operator and operator of DHB1, including its capacity-sale, market-operation, balancing, IT, and system-information functions.
C7: To	Shippers / Network Users that book or hold capacity rights and arrange hydrogen transport through DHB1.
C8: Requirements	Provide transparent, nondiscriminatory capacity terms, tariffs, and system information; require shippers to meet booking, payment, nomination, and balancing conditions. Publish restrictions and procedures for managing booked capacity and flows.
C9: Criticality	+2
C10: High-level function	Enable transparent, non-discriminatory, and operationally compatible use of DHB1 by shippers, supporting reliable hydrogen transport from production and domestic entry points to consumption and export points.
C11: Interdependency	Logical interdependency. Shipper access to DHB1 depends on capacity agreements, market rules, tariff arrangements, nomination procedures, and balancing obligations set by Energinet.
C12: Principal risks	Tariff, capacity, or contract terms may not fit shippers and may reduce bookings. Unclear nomination, balancing, or information procedures can delay responses and increase balancing actions or curtailment. Market-system failure or weak cybersecurity can impede booking and communication; regulatory changes may alter conditions underlying commitments.
C13: Uncertainty categories	Demand and market uncertainty; policy and regulatory uncertainty; infrastructure and project-delivery uncertainty; financing and investment uncertainty; technology-performance uncertainty.
C14: Uncertainty level	4
C15: Vulnerability assessment	3

Organizational Interfaces (continued)

Field	Assessment
O2: Energinet (HTNO / DHB1 owner) – Direct Producers at IE stations.	
C1: Interface ID	O2
C3: Interaction scenario	Direct hydrogen producers connect to DHB1 through Energinet-owned I/E stations to inject hydrogen under agreed technical, safety, and operational conditions. Producers own or arrange the connection facility and operate it under the connection agreement. A producer may also act as a shipper; where a separate shipper is used, the producer must coordinate relevant production information with that shipper for capacity,
C3: Interaction scenario (cont.)	nomination, and balancing purposes.
C4: Exchange type	Information (I)
C5: Interaction function	Establish and maintain the contractual, technical, and operational conditions that allow direct hydrogen producers to connect safely to DHB1 and inject hydrogen within agreed limits.
C6: From	Energinet as Hydrogen Transmission Network Operator.
C7: To	Direct hydrogen producers
C8: Requirements	Producers provide project, location, capacity, timing, injection, storage, and technical information. Specify connection limits for pressure, temperature, quality, flow, ramping, safety, and cutoff. Energinet owns the I/E station; producers or third parties own the connection facility. Agreements allocate cost, maintenance, data, alarms, isolation, incidents, and restoration.
C9: Criticality	+2
C10: High-level function	Enable safe, non-discriminatory, and operationally compatible injection of hydrogen from direct producers into DHB1 through I/E stations.
C11: Interdependency	Logical interdependency. Producer access to DHB1 depends on connection agreements, technical access conditions, ownership and cost allocation, operating responsibilities, and arrangements for curtailment or return to service.
C12: Principal risks	Disputes over connection location, design, costs, agreements, or commissioning can delay producer access. Unclear or changing technical conditions can increase costs or weaken confidence. Ambiguous data, maintenance, alarm, isolation, curtailment, or return-to-service responsibilities can delay restrictions and restoration.
C13: Uncertainty categories	Infrastructure and project-delivery uncertainty; demand and market uncertainty; policy and regulatory uncertainty; financing and investment uncertainty.
C14: Uncertainty level	5
C15: Vulnerability assessment	4

Organizational Interfaces (continued)

Field	Assessment
O3: Energinet (HTNO) – Gasunie Deutschland (Hyperlink 3 / German hydrogen TSO)	
C1: Interface ID	O3
C3: Interaction scenario	Energinet and Gasunie Deutschland coordinate the development of DHB1 and Hyperlink 3 as a connected Danish–German hydrogen corridor. The relationship covers cross-border routing and interface design, development schedules, capacity planning and booking coordination, investment and construction agreements, responsabilities at the border, and the alignment of market commitments required to progress the two projects
C3: Interaction scenario (cont.)	toward commissioning
C4: Exchange type	Information (I)
C5: Interaction function	Coordinate decisions, plans, commitments, and information required to develop DHB1 and Hyperlink 3 as a compatible and timely Danish-German hydrogen transport corridor.
C6: From	Energinet as Hydrogen Transmission Network Operator and developer of Danish Hydrogen Backbone 1.
C7: To	Gasunie Deutschland as developer/operator of Hyperlink 3 and the connected German hydrogen-network infrastructure.
C8: Requirements	Exchange project, border-design, capacity, scheduling, and dependency information. Assign development, construction, ownership, and capacity responsibilities in agreements. Coordinate bookings, demand, and German receiving capacity; communicate material changes in scope, timing, permits, funding, or commitments.
C9: Criticality	+2
C10: High-level function	Enable timely and coordinated realization of a compatible Danish–German hydrogen transport corridor connecting DHB1 with Hyperlink 3.
C11: Interdependency	Logical interdependency. The Danish–German corridor depends on bilateral agreements, allocation of responsibilities, coordinated investment and construction decisions, capacity commitments, and cross-border development arrangements between Energinet and Gasunie Deutschland.
C12: Principal risks	Different permitting, construction, or commissioning schedules can leave one national system ready before the other. Mismatched demand, booking, or capacity commitments can limit usable exports. Disagreements about investment, border ownership, construction, design, or costs may delay or require redesign; regulatory, approval, or funding changes may alter scope or timing.
C13: Uncertainty categories	Infrastructure and project-delivery uncertainty; demand and market uncertainty; policy and regulatory uncertainty; financing and investment uncertainty.
C14: Uncertainty level	5
C15: Vulnerability assessment	5

Organizational Interfaces (continued)

Field	Assessment
O4: Energinet (HTNO) – Danish Utility Regulator (DUR)	
C1: Interface ID	O4
C3: Interaction scenario	Energinet develops and, where required, submits hydrogen-network methodologies and supporting information for regulatory assessment under the Danish and EU hydrogen-market framework. The Danish Utility Regulator makes decisions within its legal competence, including on revenue-cap regulation and methodologies requiring approval. Energinet then implements the applicable approved or notified arrangements in its
C3: Interaction scenario (cont.)	tariffs, capacity-sale processes, balancing framework, and other market conditions for DHB1.
C4: Exchange type	Information (I)
C5: Interaction function	Provide the regulatory decisions, oversight, and methodological framework required for Energinet to offer transparent, non-discriminatory, and economically sustainable access to DHB1.
C6: From	Energinet (HTNO / DHB1 system operator)
C7: To	Danish Utility Regulator (DUR)
C8: Requirements	Provide information for revenue-cap regulation and implement applicable decisions. Develop, consult on, and submit methodologies for tariffs, capacity, congestion, balancing, and connection costs as required. Publish applicable arrangements; the regulator decides within its competence and monitors compliance.
C9: Criticality	+2
C10: High-level function	Enable a transparent, legally compliant, and economically sustainable regulatory framework for access to and use of DHB1.
C11: Interdependency	Logical interdependency. Energinet's implementation of relevant hydrogen-market arrangements depends on statutory responsibilities, methodology submission, consultation, regulatory decisions, and oversight by the Danish Utility Regulator.
C12: Principal risks	Delayed methodology development, consultation, assessment, or approval may slow market arrangements. Regulatory decisions or revisions can change tariffs, capacity products, balancing, or connection costs after commitments are planned. Uncertain revenue and cost allocation can discourage booking; inconsistent implementation or communication can lead to disputes or unequal treatment.
C13: Uncertainty categories	Policy and regulatory uncertainty; financing and investment uncertainty; demand and market uncertainty.
C14: Uncertainty level	4
C15: Vulnerability assessment	4

Organizational Interfaces (continued)

Field	Assessment
O5: Energinet (Electricity TSO) – PtX developer/operator	
C1: Interface ID	O5
C3: Interaction scenario	PtX developers and operators engage with Energinet as electricity TSO to obtain and use a transmission-grid connection for electrolysis. The relationship covers connection capacity and point, reinforcement requirements and timing, access conditions, possible curtailment or limited-access arrangements, protection coordination, tariffs, data exchange, and operational communication relevant to the plant's electricity
C3: Interaction scenario (cont.)	supply and flexibility.
C4: Exchange type	Information (I)
C5: Interaction function	Establish the contractual, technical, and operational conditions under which a PtX plant can connect to and use the electricity transmission grid while maintaining electricity-system security and providing a basis for planned hydrogen production.
C6: From	Energinet as electricity transmission system operator
C7: To	PtX developer/operator seeking electricity-grid access for electrolyzers and associated PtX facilities.
C8: Requirements	Specify connection point, voltage, capacity, reinforcements, timing, costs, and commissioning. Clarify full or limited access, curtailment, ramping, and tariffs. Coordinate protection, metering, data, outages, reconnection, and restart under transparent and nondiscriminatory conditions.
C9: Criticality	+2
C10: High-level function	Enable timely, transparent, and operationally compatible electricity-grid access for PtX hydrogen-production projects that may supply DHB1.
C11: Interdependency	Logical interdependency. PtX grid access depends on connection agreements, capacity allocation, reinforcement planning, access-product conditions, curtailment arrangements, tariffs, and defined operational responsibilities between Energinet and the PtX developer/operator.
C12: Principal risks	Delayed grid studies, reinforcement, permits, or commissioning can postpone PtX production. Restrictive or uncertain tariffs, access, or curtailment may weaken investment. Poor coordination of protection, outages, reconnection, or restart can prolong interruption; mismatched PtX, grid, and DHB1 schedules may leave capacity underused.
C13: Uncertainty categories	Infrastructure and project-delivery uncertainty; financing and investment uncertainty; supply and resource uncertainty; policy and regulatory uncertainty.
C14: Uncertainty level	4
C15: Vulnerability assessment	3

Sources for the organizational interfaces assessments: (Energinet, n.d., 2024a, 2024d, 2025b, 2025c, 2025d, 2026a, 2026c; Gasunie Deutschland Transport Services GmbH, 2026).

B

Technical Decomposition of DHB1

Table B.1: Technical decomposition of Danish Hydrogen Backbone 1.

Component / field	Description
Main Pipelines	
New Bramming–Veerst hydrogen pipeline	
Location	New-build transmission pipeline of approximately 41 km between PLR Bramming and PLR Veerst in western Jutland.
Function	Forms the upstream section of DHB1 and transports hydrogen from the western production area toward Veerst and the southbound export corridor. The pipeline also contributes to system linepack and operational flexibility.
Main elements and current design	Approx. 41 km new pipeline ; Operating-pressure range: 50–90 barg ; Maximum operational pressure variation: 30 bar. ; Part of the pressure range is reserved for operational security ; Approx. 90 cm diameter, detailed design is still under development
Repurposed Veerst–Frøslev pipeline	
Location	Existing gas transmission pipeline of approximately 89 km between PLR Veerst and PLR Frøslev at the Danish–German border. Originally constructed in 2011 and planned for conversion to hydrogen service.
Function	Forms the downstream Danish export section of DHB1 and transports hydrogen from Veerst toward Germany.
Main elements and current design	Approx. 89 km repurposed transmission pipeline ; Operating-pressure range: 35–58 barg ; Maximum operational pressure variation: 10 bar ; Connected to MRS Veerst upstream and the southern metering/export infrastructure downstream ; line-valve stations provide sectionalization along the route.
Stations On The Mainline	
Pig Launcher and Receiver (PLR) facilities	
Location	A PLR station is planned at Bramming.
Function	Enable insertion and retrieval of pipeline inspection/cleaning devices and support isolation, maintenance, commissioning and controlled depressurization of pipeline sections.

Technical decomposition (continued)

Component / field	Description
Main elements and current design	Pig launcher/receiver facilities ; Main isolation valve where applicable ; Associated venting arrangements ; Provisions for future network extensions or connection facilities at relevant locations.
Mainline Regulator Station (MRS), Veerst	
Location	At Veerst, where the new Bramming–Veerst pipeline connects to the repurposed Veerst–Frøslev pipeline.
Function	Manages the transition between the higher-pressure new-build section and the lower-pressure repurposed section by regulating pressure and flow.
Main elements and current design	Pressure reduction ; Flow control ; Overpressure protection ; Vent stacks ; PLR facilities for the westbound and southbound pipelines ; Prepared for future I/E facilities ; Space reserved for possible future eastward network extension.
Mainline Metering Station (MMS), Padborg	
Location	At Padborg, close to the Danish–German border and the southern end of DHB1.
Function	Measures hydrogen flow and quality toward Germany and supports pressure and flow control functions prior to cross-border transport.
Main elements and current design	Flow measurement ; Hydrogen-quality measurement ; Pressure and flow regulation ; Overpressure protection ; Main valve and vent stack ; PLR facilities to the north and south ; Provision for an I/E station.
Line Valve Stations (line-valve stations)	
Location	Six stations distributed along the new and repurposed pipeline sections, with spacing of no more than approximately 24 km along the pipeline.
Function	Section the transmission pipeline so that individual sections can be isolated during maintenance or incidents, reducing the length of pipeline affected by an intervention.
Main elements and current design	Main sectionalizing valve ; Associated vent stack ; Prepared for later installation of I/E facilities where required.
Connection Facilities At User Interfaces	
Injection or Extraction Station (I/E station – Energinet)	
Location	May be established at the nine identified DHB1 station locations: Bramming, Glejbjerg, Veerst, Lunderskov, Sommersted, Agerskov, Klovtoft, Tinglev and Padborg, depending on concluded connection agreements.
Function	Forms the transmission-side connection between a user and DHB1 and provides the measurement, regulation and safety functions required for hydrogen injection or extraction.
Main elements and current design	Each individual station is dedicated to a user and handles either injection or extraction ; Measurement and regulation functions ; Flow and hydrogen-quality measurement/validation by Energinet ; Operational data and signal exchange with connected users ; Energinet owns the I/E station; associated connection costs are charged to the user ; Land initially reserved for two stations at each connection point.
User-side connection facility	
Location	Between the producer, consumer or storage facility and the relevant Energinet I/E station.
Function	Provides the physical link through which hydrogen is transferred between the user's facility and DHB1.

Technical decomposition (continued)

Component / field	Description
Main elements and current design	Owned and operated by the user or by a third party on the user's behalf ; Connection facility/pipeline to the Energinet I/E station ; Technical configuration depends on the individual user, connection requirements and detailed design ; Interface conditions are developed through the pre-construction and connection-agreement process.
Cross-Border And External Network Components	
Danish–German cross-border interface	
Location	Southern DHB1 corridor around Padborg/Frøslev–Ellund, connecting the Danish transmission system with the German hydrogen system.
Function	Enable the transfer of hydrogen from DHB1 into the German transmission network and therefore constitutes the principal downstream boundary of the Danish system studied in this thesis.
Main elements and current design	Southbound physical hydrogen export ; Pressure, flow, quality and available capacity must be compatible across the border ; Danish export measurement and quality functions are associated with the Padborg MMS ; Current DHB1 design does not provide normal physical northbound transport; northbound service is described by Energinet as interruptible commercial backhaul.
Gasunie Deutschland Hyperlink 3	
Location	German transmission project extending toward the Danish interconnection at Ellund and southward through northern Germany.
Function	Receives hydrogen from the Danish corridor and provides onward transport into the German hydrogen network and demand areas. It is treated as an external receiving system, not as a Danish DHB1 asset.
Main elements and current design	Current Gasunie route: Heidenau–Stade–Elbe Süd–Ellund ; Published transmission capacity: 2.5–4.3 GW, with expansion possible ; Development currently indicated for 2028–2031 ; Current Gasunie information states that the extension to Ellund depends on demand and Danish-network availability.
Measurement, Control And Data Systems	
I/E-station metering and operational data exchange	
Location	At I/E stations and across the Energinet–user connection boundary.
Function	Measure and validate hydrogen entering or leaving DHB1 and provide the operational information required for coordinated operation of the connection.
Main elements and current design	Hydrogen-flow measurement and validation ; Hydrogen-quality measurement and validation ; Exchange of relevant signals and operational data between Energinet and connected users ; Detailed procedures for off-specification events, signaling and data exchange to be established in connection agreements.
Operational monitoring and SCADA	
Location	Across DHB1's station and central operational-control environment.
Function	Supports centralized monitoring and control of operating conditions and station functions across the transmission system.
Main elements and current design	A new SCADA system is included in the DHB project ; Operational measurements, alarms and status information form part of system operation ; Detailed system architecture has not been publicly specified.

Technical decomposition (continued)

Component / field	Description
Balancing and linepack information system	
Location	System-level information environment linking physical pipeline conditions with shipper and balancing activities.
Function	Provides Energinet and shippers with information needed to manage system balance and use the physical linepack flexibility of DHB1.
Main elements and current design	Available system linepack flexibility, including reserve and shipper-designated flexibility ; System-wide and individual shipper balance positions ; Daily and near-real-time information on flexibility and system balance ; Information supporting balancing actions and controlled cut-off when operational limits are exceeded
Safety And Auxiliary Systems	
Venting and controlled depressurization systems	
Location	Associated with PLR facilities, MRS Veerst, Padborg MMS, line-valve stations and relevant I/E facilities.
Function	Allow controlled pressure reduction and hydrogen release during isolation, maintenance, commissioning and abnormal operating conditions.
Main elements and current design	Vent stacks associated with main DHB1 station types ; Venting/flaring arrangements must be designed so that their effects do not compromise adjacent facilities ; For the specified adjacent PLR configuration, Energinet gives a maximum heat-radiation criterion of 4.7 kW/m² at the relevant DHB1 boundary.
Overpressure protection and isolation systems	
Location	At MRS Veerst, MMS Padborg, line-valve stations and relevant connection/station interfaces.
Function	Protect the transmission system from unacceptable pressure conditions and enable pipeline sections or connected facilities to be isolated when required.
Main elements and current design	Overpressure protection at MRS/MMS ; Main isolation/sectionalizing valves ; line-valve stations for pipeline sectionalization ; Double isolation and bleed (DIB), or equivalent isolation, required in the specific adjacent-PLR arrangement described by Energinet.
Safety layout and below-ground equipment requirements at adjacent facilities	
Location	At interfaces where PLR or other hydrogen facilities are located adjacent to DHB1 installations.
Function	Reduce escalation risk between adjacent hydrogen installations and DHB1 equipment.
Main elements and current design	Minimum safety distances between DHB1 and adjacent hydrogen facilities ; Below-ground placement of hydrogen-containing equipment where required for safety ; PLR hatches oriented away from DHB1 equipment and facilities ; Site-specific risk assessment for adjacent hydrogen installations

sources for the decomposition: (Danish Energy Agency, 2025; Energinet, 2025a, 2025c; Gasunie Deutschland Transport Services GmbH, 2026).

C

Qualitative Vulnerability and Uncertainty Assessment

C.1. Assessment Criteria

Table C.1: Vulnerability assessment criteria.

Assessment dimension	Score	Meaning
Degree of functional disruption	0	Limited local disruption. A disruption would affect only the immediate interface or a local function, without materially restricting hydrogen entry, transport, delivery, access, balancing, or the ability of other users to operate.
	1	Partial or temporary reduction in function. A disruption could restrict injection, reduce transport capacity, delay access, or require additional operational intervention, without necessarily causing substantial or prolonged loss of a core system function.
	2	Substantial or prolonged loss of a core function. A disruption could prevent an essential pressure transition, block the export corridor, or substantially impair safe transport, delivery, or system-wide balancing. Loss of function may also propagate to connected interfaces.
Availability of alternative capacity or recovery paths	0	Effective alternative available. A technically, operationally, or organizationally feasible alternative can maintain the required function with little or no material loss of capacity, safety, quality, or service. Examples may include redundant equipment, an alternative route, reserve capacity, a validated backup system, or a pre-agreed substitute procedure.

Table C.1: Vulnerability assessment criteria (continued).

Assessment dimension	Score	Meaning
	1	Partial alternative available. A workaround exists but provides only reduced capacity, reduced flexibility, delayed recovery, additional cost, manual operation, or restricted service. The required function can continue only partially or temporarily.
	2	No feasible alternative within the required time frame. No redundant asset, alternate route, reserve capacity, backup procedure, or substitute contractual arrangement can maintain the required function within the necessary response time. The interface therefore acts as a single point of failure for that function.
Adequacy of protection and mitigation	0	Protection is documented and sufficiently defined for the assessed failure mode. Preventive and corrective functions are technically established, responsibility is identified, and the available requirements or design provisions provide a credible basis for timely response. Examples include specified automatic protection, local alarms, isolation, and safe-state functions.
	1	Protection is identified but has important limitations. Measures can prevent or limit disruption, but effectiveness depends on incomplete interface-specific arrangements, manual action, inter-organizational coordination, uncertain response time, or performance not established for the relevant integrated scenario.
	2	Protection is absent or insufficiently defined for the scenario. No credible preventive or corrective arrangement is identified, or major gaps in coverage, responsibility, technical capability, or response time leave the assessed failure mode inadequately addressed.

Table C.2: Uncertainty assessment criteria.

Assessment dimension	Score	Meaning
Evidence specificity and reliability	0	Direct evidence. The assessment is supported by current DHB1-specific technical specifications, approved methods, contractual requirements, detailed design information, or directly applicable standards. The evidence identifies the relevant interface, condition, and requirement with little need for inference.

Table C.2: Uncertainty assessment criteria (continued).

Assessment dimension	Score	Meaning
	1	Partly direct evidence with justified transfer. The assessment is informed by some DHB1-specific information but relies partly on evidence transferred from comparable systems, such as the Danish methane network, established hydrogen standards, comparable pipelines, or relevant pilot projects. The transfer is reasonable but depends on assumptions about similarity of conditions.
	2	Limited direct evidence; assumption-dependent assessment. There is little or no interface-specific evidence. The assessment depends mainly on preliminary plans, expert judgment, analogies, scenarios, or unresolved design, market, regulatory, or operational assumptions.
Variability of future operating conditions	0	Conditions are defined and bounded. The relevant operating, contractual, or regulatory conditions are specified and expected to remain within a narrow range. Examples include established pressure limits, fixed design requirements, approved methods, or clearly defined connection obligations.
	1	Conditions may vary within known limits. The interface is expected to experience variation in flows, demand, production, load, operating schedules, or market behavior, but the main range of variation and the principal response arrangements are known.
	2	Conditions are not yet defined or may vary substantially. Key future conditions depend on uncertain project delivery, market uptake, producer behavior, regulation, cross-border arrangements, technology performance, financing, or system configuration. Plausible scenarios may differ materially in scale, timing, or operating behavior.
Observability and controllability of deviations	0	A well-defined basis exists for prompt detection and correction. Relevant measurement, alarm, local control, and safe-state functions are documented, responsibility is identified, and established response functions can address the deviation within the required time.
	1	Detection or correction is delayed or partly dependent on coordination. Relevant variables are monitored, but data may be periodic, incomplete, delayed, or require manual validation. Corrective action is available but may require communication between actors, manual intervention, or actions that reduce capacity or service.

2	Deviations are difficult to detect, diagnose, or correct. Monitoring is absent, incomplete, unvalidated, or not yet defined; warning signals may be delayed or ambiguous; or no clearly assigned actor has the authority, technical capability, or agreed procedure to correct the deviation within the required response time.

Table C.3: Classification thresholds for the sum of three dimension scores.

Assessment	Total	Classification and interpretation
Vulnerability	0–2	Less vulnerable: the combined rating indicates comparatively limited vulnerability, although a constraint may remain in an individual dimension.
Vulnerability	3–4	Vulnerable: the combined rating reflects functional disruption, limited alternatives, and/or limitations in protection.
Vulnerability	5–6	Very vulnerable: the combined rating reflects major limitations across the dimensions, such as substantial loss of function together with absent alternatives or insufficient protection.
Uncertainty	0–2	Low: the combined rating indicates relatively well-defined conditions and a stronger basis for assessment or control, although a gap may remain in one dimension.
Uncertainty	3–4	Medium: the combined rating reflects reliance on transferred evidence, future variation, and/or delayed or partial control.
Uncertainty	5–6	High: major uncertainty is present across the dimensions, involving limited direct evidence, substantially variable conditions, and/or restricted detection and correction.

C.2. Interface-Level Assessment Results

The shortened column headings in Table C.4 mean *degree of functional disruption* (F), *availability of alternative capacity or recovery paths* (A), and *adequacy of protection and mitigation* (P), respectively. In Table C.5, they mean *evidence specificity and reliability*, *variability of future operating conditions*, and *observability and controllability of deviations*. The full criteria appear in Tables C.1 and C.2. T1–T10 and O1–O5 are the technical and organizational interface identifiers used in Chapter 5 and Appendix A. Condensed justifications for every dimension score are provided in Section C.3.

Table C.4: Vulnerability assessment results by interface.

ID	Functional disruption	Alternatives	Protection	Total	Classification
Technical interfaces					
T1	2	2	1	5	Very vulnerable

Table C.4: Vulnerability assessment results by interface (continued).

ID	Functional disruption	Alternatives	Protection	Total	Classification
T2	1	1	0	2	Less vulnerable
T3	1	1	1	3	Vulnerable
T4	2	2	1	5	Very vulnerable
T5	2	2	1	5	Very vulnerable
T6	1	1	0	2	Less vulnerable
T7	1	2	1	4	Vulnerable
T8	1	1	1	3	Vulnerable
T9	1	2	1	4	Vulnerable
T10	2	2	1	5	Very vulnerable
Organizational interfaces					
O1	1	1	1	3	Vulnerable
O2	1	2	1	4	Vulnerable
O3	2	2	1	5	Very vulnerable
O4	1	2	1	4	Vulnerable
O5	1	1	1	3	Vulnerable

Table C.5: Uncertainty assessment results by interface.

ID	Evidence	Variability	Control	Total	Classification
Technical interfaces					
T1	1	1	1	3	Medium
T2	1	1	0	2	Low
T3	1	2	2	5	High
T4	1	1	1	3	Medium
T5	1	2	1	4	Medium
T6	0	1	0	1	Low
T7	2	2	1	5	High
T8	2	2	1	5	High
T9	2	2	1	5	High
T10	1	2	1	4	Medium
Organizational interfaces					
O1	1	2	1	4	Medium
O2	2	2	1	5	High
O3	1	2	2	5	High
O4	1	2	1	4	Medium
O5	1	2	1	4	Medium

C.3. Condensed Justifications for Dimension Scores

Tables C.6 and C.7 explain the individual 0-2 scores in relation to the interface functions, risks, and conditions described in Chapter 5 and Appendix A.

C.3.1. Vulnerability

Table C.6: Condensed justifications for the vulnerability dimension scores.

ID	Dimension	Score	Condensed justification
T1	Functional disruption	2	Prolonged loss of the Bramming operational boundary could prevent use of the new pipeline section and substantially restrict southbound transport and export.
	Alternatives	2	No parallel upstream operational boundary or equivalent route into the new pipeline section is identified in the initial configuration.
	Protection	1	Isolation, venting, overpressure protection, monitoring, and response arrangements provide safeguards, but final procedures and integrated hydrogen-service performance require validation.

Table C.6: Condensed justifications for the vulnerability dimension scores (continued).

ID	Dimension	Score	Condensed justification
T2	Functional disruption	1	A valve fault can impair sectional isolation or restoration and extend local curtailment, without necessarily disabling transport through the entire corridor.
	Alternatives	1	Neighbouring valve stations may support isolation of a larger section, with reduced flexibility and potentially longer outages.
	Protection	0	Code-based valve protection, inspection, testing, monitoring, and operating procedures are assessed as sufficient for the identified isolation and venting scenarios.
T3	Functional disruption	1	A station problem can restrict its connected user's injection or withdrawal and affect nearby operating conditions, without necessarily stopping the export corridor.
	Alternatives	1	Other entry points or operational workarounds may preserve some system supply, but cannot necessarily replace the affected user's access or timing.
	Protection	1	Measurement, quality validation, monitoring, and cut-off are planned, but connection-specific protection and incident procedures remain incomplete.
T4	Functional disruption	2	Sustained inability to transfer hydrogen into MRS Veerst would interrupt the essential pressure-transition pathway from the new pipeline to the converted export section.
	Alternatives	2	No parallel MRS or alternative pressure-staging route is identified in the initial configuration.
	Protection	1	Regulation, overpressure protection, isolation, venting, and alarms provide safeguards, but integrated performance in the final hydrogen regime remains unproven.
T5	Functional disruption	2	Sustained loss of the MRS outlet could prevent onward transport into the converted pipeline and substantially restrict the southbound export function.
	Alternatives	2	No parallel MRS outlet or equivalent downstream route to Padborg/Ellund is identified.
	Protection	1	Pressure reduction, flow control, monitoring, isolation, and overpressure protection limit escalation, but final hydrogen-service performance requires validation.
T6	Functional disruption	1	Station-level SCADA loss can impair supervision and control or require local operation or cut-off, normally restricting one connection rather than the full corridor.
	Alternatives	1	Local instrumentation, protection, manual intervention, and isolation provide partial substitutes, but do not fully replace central supervision or the user's connection.
	Protection	0	Measurement, quality monitoring, alarms, local protection, isolation, and safe-state functions are assessed as sufficient safeguards for the station-level loss-of-supervision scenario.

Table C.6: Condensed justifications for the vulnerability dimension scores (continued).

ID	Dimension	Score	Condensed justification
T7	Functional disruption	1	Production-side failure can interrupt delivery from one producer and reduce available hydrogen entry, without necessarily disabling transport by the wider backbone.
	Alternatives	2	The individual producer has no identified timely alternative to its production-to-connection-pipeline delivery path.
	Protection	1	Conditioning, monitoring, alarms, buffering, isolation, and connection arrangements provide partial protection, but their final integrated performance remains to be demonstrated.
T8	Functional disruption	1	Electricity interruption reduces the affected PtX plant's production and hydrogen supply to DHB1, without necessarily stopping backbone transport if other supply remains available.
	Alternatives	1	Hydrogen storage, linepack, flexible operation, and other producers may partly maintain supply, without immediately replacing the lost electricity connection.
	Protection	1	Grid and plant protection, disconnection, communication, and restart arrangements limit escalation, but cannot guarantee electricity availability or coordinated recovery.
T9	Functional disruption	1	A connection fault can stop one producer's injection and require intervention, but normally leaves the wider backbone available with reduced supply.
	Alternatives	2	No alternative service line or I/E station is identified that could maintain the same producer's injection within the required response time.
	Protection	1	Validation, regulation, and isolation limit unsafe injection, but response and restoration depend on producer–Energinet coordination and may interrupt service.
T10	Functional disruption	2	Sustained loss of delivery into Padborg MMS would block the identified final Danish export path and substantially impair DHB1's core cross-border delivery function.
	Alternatives	2	No parallel pipeline or equivalent route from the converted section into Padborg MMS is identified.
	Protection	1	Regulation, metering, quality measurement, isolation, and venting limit escalation, but cannot maintain export through a seriously impaired station inlet.
O1	Functional disruption	1	Unclear or unsuitable capacity, nomination, or balancing arrangements can restrict users' effective access and coordinated use of transport capacity, without necessarily disabling physical transport.
	Alternatives	1	Revised products, procedures, balancing actions, or controlled cut-off may preserve security, but reduce service and do not immediately restore commitments.
	Protection	1	Contracts, market systems, regulated access, information, and oversight provide safeguards, but depend on final procedures, compliance, and effective balancing actions.

Table C.6: Condensed justifications for the vulnerability dimension scores (continued).

ID	Dimension	Score	Condensed justification
O2	Functional disruption	1	Delayed or disputed connection arrangements can prevent one producer's access or restart, reducing available injection without normally disabling transport by the wider backbone.
	Alternatives	2	A producer cannot substitute Energinet's connection approval and operating agreement with an equivalent timely organizational route to DHB1.
	Protection	1	Structured connection processes and agreements clarify responsibilities, but cannot eliminate delays, disputes, redesign, or mismatched project schedules.
O3	Functional disruption	2	Failed cross-border development coordination can prevent the Danish and German networks from providing a continuous export corridor, leaving DHB1 unable to perform its central export function.
	Alternatives	2	No near-term alternative provides an equivalent high-volume pipeline connection to Germany at comparable capacity and timing.
	Protection	1	Bilateral agreements, planning, market dialogue, and decision gates improve coordination, but cannot ensure commitments, permits, funding, or synchronized delivery.
O4	Functional disruption	1	Delayed or revised methodologies can postpone the implementation of access, tariff, or balancing arrangements and restrict effective use of capacity, without necessarily disabling the physical corridor.
	Alternatives	2	No alternative regulator or parallel legal approval route can provide the required Danish methodology decisions; resubmission is not an immediate substitute.
	Protection	1	Consultation, publication, regulatory decisions, and resubmission provide safeguards, but cannot guarantee decision timing, prevent legal change, or avoid market effects.
O5	Functional disruption	1	Delayed or restrictive grid-access arrangements can prevent or reduce an individual PtX plant's hydrogen production, limiting supply to DHB1 without necessarily stopping backbone transport.
	Alternatives	1	Rescaling, different access arrangements, flexible operation, storage, or relocation may preserve part of the objective, with added cost or delay.
	Protection	1	Formal connection planning, technical requirements, risk allocation, and coordination manage exposure, but cannot guarantee reinforcement timing or uninterrupted supply.

C.3.2. Uncertainty

Table C.7: Condensed justifications for the uncertainty dimension scores.

ID	Dimension	Score	Condensed justification
T1	Evidence	1	DHB1 documents define the station, route, pressure range, and quality requirements, but detailed operational arrangements remain preliminary.
	Variability	1	Injection, linepack, and start-up conditions may vary within an already defined broad function and operating envelope.
	Control	1	Instrumentation and isolation permit intervention, but final operating philosophy, integrated response, and demonstrated service performance remain incomplete.
T2	Evidence	1	Established codes and DHB1 limits support the assessment, but long-term evidence for the specific hydrogen-service isolation and venting regime is limited.
	Variability	1	Isolation and venting frequency depend on maintenance and incidents, but the principal duty and operating range are relatively predictable.
	Control	0	Valve status and operating conditions are monitorable, with defined isolation and venting actions assessed as enabling prompt detection and correction.
T3	Evidence	1	Station purpose, potential locations, preliminary quality limits, and measurement responsibilities are documented, but detailed designs and agreements remain incomplete.
	Variability	2	The stations built, connected users, capacity, injection or withdrawal patterns, and operating profiles remain dependent on future projects.
	Control	2	Detailed data exchange, alarm responsibilities, cut-off arrangements, and response procedures remain under development, limiting confidence in timely coordinated correction.
T4	Evidence	1	Codes and DHB1 limits provide a basis, but the specific new-pipeline–MRS–converted-pipeline configuration lacks sustained operating experience.
	Variability	1	Inlet pressure and flow vary with production and export operation within the defined broad pipeline and station envelope.
	Control	1	Regulation and protection provide intervention options, but coordinated performance under the final operating regime has not been demonstrated.
T5	Evidence	1	The converted route, broad pressure limits, and MRS function are documented; detailed outlet settings and operating philosophy remain incomplete.
	Variability	2	Early flow, linepack use, production, bookings, and downstream conditions may differ substantially across plausible operating scenarios.
	Control	1	Monitoring, regulation, isolation, and venting provide control, but integrated response under final hydrogen conditions remains unvalidated.

Table C.7: Condensed justifications for the uncertainty dimension scores (continued).

ID	Dimension	Score	Condensed justification
T6	Evidence	0	DHB1 documentation directly assigns flow and quality measurement to Energinet and identifies operational data and signal exchange at I/E stations.
	Variability	1	The basic monitoring function is stable, while signal lists, users, data volumes, and control arrangements vary by connection.
	Control	0	Monitoring, alarms, local control, isolation, and safe-state functions are assessed as providing prompt station-level detection and corrective options.
T7	Evidence	2	The specific large-scale PtX-to-pipeline configuration is supported mainly by preliminary project information rather than sustained interface-specific operating evidence.
	Variability	2	Production, ramping, availability, and delivery profiles depend strongly on electricity prices, off-take arrangements, policy support, and plant design.
	Control	1	Metering, alarms, and data exchange are planned, but detailed implementation and coordinated incident-management experience remain limited.
T8	Evidence	2	The assessment lacks final plant-specific electrical connection, protection, capacity, and integrated operating details, making it dependent on preliminary assumptions.
	Variability	2	Available electricity, curtailment, connection timing, and plant operating profiles can differ substantially across future grid and production conditions.
	Control	1	Protection, metering, and operational communication support response, but correction may require coordination and cannot promptly remove congestion or supply restrictions.
T9	Evidence	2	Generic station requirements are known, but final producer-specific design, handover, operating envelope, control logic, and executed agreements are unavailable.
	Variability	2	Project timing, capacity, injection profiles, pressure conditions, ramping, and users at a location may change substantially during development.
	Control	1	Measurement, regulation, and isolation improve control, but final authority, data exchange, and incident procedures require connection-specific agreement.
T10	Evidence	1	Route, pressure limits, and MMS functions are documented; sustained integrated hydrogen behaviour is partly inferred from comparable gas practice and standards.
	Variability	2	Flows, producer injections, nominations, linepack, maintenance, and border conditions remain materially variable during early operation.
	Control	1	Monitoring and regulation permit correction, but response may require upstream coordination, curtailment, or controlled shutdown.

Table C.7: Condensed justifications for the uncertainty dimension scores (continued).

ID	Dimension	Score	Condensed justification
O1	Evidence	1	Capacity sales and shipper roles are documented, while detailed operating arrangements partly rely on preliminary proposals and methane-market experience.
	Variability	2	Participation, bookings, supply, demand, production profiles, and the practical use of market arrangements remain substantially scenario-dependent.
	Control	1	Bookings and balance positions are monitorable, but correcting weak uptake or commercial misalignment requires slower contractual, product, or regulatory changes.
O2	Evidence	2	The generic connection model is documented, but final producer-specific agreements, detailed operating conditions, and sustained service evidence remain unavailable.
	Variability	2	Producer number, timing, location, scale, technology, availability, and commercial maturity may materially alter connection arrangements and supply.
	Control	1	Station controls support safe operation, but connection delays, cancellations, and disputes require negotiation and cannot be corrected rapidly.
O3	Evidence	1	The corridor, routes, capacity processes, and agreement structure are documented, but final agreement implementation and successful joint delivery remain unsettled.
	Variability	2	Bookings, demand, funding, permits, construction, and downstream readiness can materially change corridor capacity, scope, timing, and viability.
	Control	2	Neither TSO can independently control the other system's delivery or external approvals and commitments; resolving major misalignment may require lengthy redesign or investment decisions.
O4	Evidence	1	Published methods and regulatory decisions provide direct evidence, but tariff, balancing, and other detailed arrangements remain incompletely defined or untested.
	Variability	2	Capacity uptake, costs, interest rates, revenue allowances, support, and evolving market rules can materially change future access and investment conditions.
	Control	1	Submissions and decisions are observable and revisable, but correction requires formal processes and cannot promptly control legal, market, or cost changes.
O5	Evidence	1	Published access principles provide direct evidence, but plant-specific agreements, reinforcements, tariffs, and curtailment conditions require inference.
	Variability	2	Congestion, reinforcement timing, electricity prices, access products, curtailment, and investment decisions may materially alter the project's operating conditions.

Table C.7: Condensed justifications for the uncertainty dimension scores (continued).

ID	Dimension	Score	Condensed justification
	Control	1	Milestones and connection terms are monitorable and negotiable, but major reinforcements, congestion, permits, and investment timing cannot be corrected rapidly.

D

Expert Contributions to the Analysis and Mitigation Measures

This appendix summarizes the experts' professional backgrounds and their contributions to the thesis through interviews guided by the preliminary cluster-analysis document. Contributions from Experts 1 and 2 are reported jointly.

D.1. Experts 1 and 2

Table D.1: Professional backgrounds and joint contributions of Experts 1 and 2.

Aspect	Description
Organization	Energinet.
Expert 1: position and expertise	Engineer working on Danish hydrogen-market development and DHB1, including capacity sales, market-participant dialogue, tariff conditions, connection processes, and commercial arrangements.
Expert 2: position and expertise	Gas-system operations specialist with experience in Danish gas-transmission operation, security of supply, balancing, and coordination with shippers.
Cluster composition	Informed the inclusion of I/E stations in Cluster 1 and the converted pipeline in Cluster 2, and clarified the pressure-regulation function of MRS Veerst.
Market access and viability	Explained that shipper behaviour depends not only on market rules but also on off-taker consumption profiles and electricity prices; highlighted the importance of capacity commitments before project realization.

Table D.1: Professional backgrounds and joint contributions of Experts 1 and 2 (continued).

Aspect	Description
Cross-border operation	Clarified that German-side restrictions affect available interconnection capacity while responsibility for restoring German assets remains with the German operator. Explained that interruptible northbound capacity makes the import limitation transparent to shippers.
Actor responsibilities	Clarified the distinction between physical producers or consumers and shippers responsible for booking, nominations, and balancing.
Mitigation measures	Informed the review of market flexibility against physical operating limits and the development of measures for communicating capacity restrictions, coordinating Danish–German maintenance and restoration, and testing operational responses before commercial operation (Sections 7.4.1–7.4.2).

D.2. Expert 3

Table D.2: Professional background and contributions of Expert 3.

Aspect	Description
Organization	Copenhagen Infrastructure Partners.
Position and expertise	Technical Safety Lead involved in large-scale PtX development, with expertise in technical safety, electricity-grid interaction, hydrogen production, export, and hydrogen buffering.
Producer connections	Expanded the analysis of connection-pipeline development to include pipeline length, land rights, routing, protected landscapes, permitting, design requirements, construction costs, and responsibility for delivery.
Safety requirements	Prompted closer consideration of the regulatory requirements for producer pipelines and their implications for connection feasibility and cost.
Operational consequences	Challenged overstated assumptions about immediate backbone pressure fluctuations and emphasized pipeline volume, linepack, and time available for intervention.
Electricity dependence	Informed the abrupt power-interruption scenario and the discussion of prolonged shortages, curtailment priorities, and restoration.
Project development	Highlighted dependence on off-taker commitments and the interdependence of producer and infrastructure investment decisions.
Mitigation measures	Informed coordinated readiness checks across the electricity connection, PtX plant, producer pipeline, and I/E station; consideration of shared producer connections; and clarification of ownership, metering, data exchange, injection, and restart responsibilities (Section 7.4.3).

D.3. Expert 4

Table D.3: Professional background and contributions of Expert 4.

Aspect	Description
Organization	Danish Utility Regulator.
Position and expertise	Specialist in gas and hydrogen-network regulation, including tariff regulation, capacity products, capacity allocation, and regulatory methodologies.
Regulatory responsibilities	Clarified the distinction between approval of methodologies, revenue-cap regulation, and determination of tariffs, informing the stakeholder description and O4 assessment.
Regulatory uncertainty	Distinguished intended market arrangements in Energinet's information packages from submitted or approved methodologies, sharpening the interpretation of uncertainty in Cluster 1.
Cross-border governance	Emphasized existing institutional coordination rather than treating cooperation between Denmark and Germany as absent, informing the framing of Cluster 2 and its mitigation discussion.
Producer flexibility	Qualified the consequences of electricity interruptions by drawing attention to electrolyzer characteristics, producer storage, and connection-pipeline linepack.
Mitigation measures	Informed the distinction between settled and unresolved market conditions, the need to respect regulatory approval processes when revising arrangements, and the consideration of producer-specific flexibility in procedures for reduced delivery and restart (Sections 7.4.1–7.4.3).

Note. Role descriptions summarize the expertise reported in Section 3.2.2. The mitigation measures are the thesis author's analytical proposals, informed by the expert contributions and documentary evidence; they are not presented as verbatim recommendations or formal endorsements by the experts.

E

Expert Interview Guide and Preliminary Cluster Analysis

This appendix reproduces the preliminary cluster-analysis document and interview guide provided to the experts before the interviews. The document presents the proposed clusters, their constituent interfaces, the rationale for grouping them, illustrative vulnerability scenarios, and the questions used to guide the expert discussions.

The preliminary document is retained in its original form to show the material on which the expert review was based. Its cluster structure and numbering therefore differ from those of the final analysis presented in Chapter 6.

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PRELIMINARY CLUSTER ANALYSIS FOR EXPERT VALIDATION

Vulnerabilities at Technical and Organizational Interfaces in Hydrogen Transport Infrastructure Systems

Case study: Danish Hydrogen Backbone 1

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1. Background and Analytical Approach

This document presents the preliminary cluster analysis developed as one of the outputs of my thesis, *Vulnerabilities at Technical and Organizational Interfaces in Hydrogen Transport Infrastructure Systems*, based on the case of Danish Hydrogen Backbone 1 (DHB1). Its purpose is to support expert discussion and validation of the identified clusters and their potential cross-level vulnerability mechanisms.

The analysis began with a technical decomposition of DHB1 into its principal assets, connections, and operational functions. A stakeholder analysis was then conducted to identify the organizations that influence the planning, access, operation, regulation, and cross-border coordination of the system. Together, these steps identified technical interfaces such as; pipelines, stations, metering systems, SCADA, and PtX connections and organizational interfaces involving Energinet, shippers, direct producers and consumers, Gasunie Deutschland, and the Danish Utility Regulator (Energinet, 2024, 2025).

Each interface was subsequently analyzed using the Interface Analysis Template (IAT) developed by Uddin et al. (2015). The IAT provides a structured approach for documenting interacting entities, interface functions, exchanges, requirements, dependencies, and criticality across different system levels. In this study, it was used to connect stakeholder-level arrangements with infrastructure-level technical interfaces.

The IAT was extended with additional fields for specific risks, uncertainty, and vulnerability assessment. Interdependencies were interpreted using the framework developed by Rinaldi et al. (2001), which identifies physical, cyber, geographic, and logical interdependencies.

Finally, the interfaces were grouped into five cross-level clusters. The clusters were not formed solely according to geographic location or asset type. Instead, they bring together interfaces that support a shared system function and exhibit related dependencies, risks, uncertainties, or potential vulnerability mechanisms. The cross-level examples presented in each cluster are analytical scenarios for discussion and validation; they do not represent confirmed future operating outcomes or established positions of Energinet, Gasunie Deutschland, the Danish Utility Regulator, or other stakeholders.

2. Cross-level clusters

2.1. Cluster 1: Backbone Access, Tariffs, and Balancing

2.1.1. Interfaces included in the cluster

This cluster focuses on the interaction between the market and regulatory arrangements governing access to Danish Hydrogen Backbone 1 (DHB1) and the physical infrastructure that enables hydrogen export through the Bramming–Veerst corridor. It includes two of the organizational interfaces. The first is the relationship between **Energinet and shippers**, which covers capacity booking, nominations, balancing responsibilities, and access to the hydrogen entry–exit system. The second is the relationship between **Energinet and the Danish Utility Regulator (DUR)**, through which Energinet develops and submits methodologies for hydrogen transport charges, capacity allocation, and balancing for regulatory approval. This also includes the proposed use of an intertemporal cost allocation mechanism during the early market-development phase (Energinet, 2024, 2025).

The cluster also includes four of the technical interfaces that form the initial export corridor. These are the interface between the **Bramming PLR/main valve station and the new Bramming–Veerst pipeline**, where inlet pressure, hydrogen quality, start-up, and line pack conditions must be managed, the interface between the **new pipeline and the line valve stations**, which enable pipeline sections to be isolated and depressurized during maintenance or incidents, the interface between the **new pipeline and the Mainline Regulator Station at Veerst**, where pressure and flow are regulated before hydrogen enters the repurposed pipeline towards Frøslev/Ellund. It also includes the **Bramming PLR–Energinet SCADA interface**, which provides telemetry, alarms, and remote-control capability for inlet operation.

Taken together, these interfaces represent the part of DHB1 where commercial access rules meet the physical export corridor from Bramming to Veerst.

2.1.2. Rationale for cluster 1

The interfaces were grouped because they share the same operational corridor, extending from Bramming through Veerst and onward to Frøslev/Ellund, and because they contribute to the common function of enabling safe and efficient hydrogen transport under an entry–exit market model.

The cluster was constructed using the IAT. The technical interfaces enable inlet operation, pressure regulation, sectionalizing, and operational control, while the organizational interfaces establish capacity booking, nominations, balancing responsibilities, tariffs, and regulatory approval.

The IAT also identifies several interdependencies shared by these interfaces. The technical interfaces involve physical dependencies, including pressure, flow, linepack, and hydrogen quality. The Bramming PLR–SCADA interface introduces information and control dependencies through telemetry, alarms, and remote operation. The Energinet–shipper and Energinet–DUR interfaces create logical dependencies through contracts, transport conditions, capacity products, balancing rules, tariff methodologies, and regulatory approvals.

Finally, the risk, uncertainty, and vulnerability fields in the IAT were used to refine the cluster. The organizational interfaces identify uncertainty surrounding transport-charge and capacity-allocation methodologies, nomination and balancing rules, and the timing or outcome of regulatory approval. The technical interfaces highlight pressure and quality requirements at Bramming and Veerst, limited linepack flexibility during early operation, start-up transients, maintenance constraints, and

dependence on reliable telemetry and control. The cluster was therefore not formed only because the interfaces are geographically connected. It was formed because the IAT indicates that their technical, commercial, regulatory, and operational dependencies can interact along the same export corridor.

2.1.3. Cross-level vulnerabilities in this cluster

Market design affects the operational pressure on the corridor

Market rules, concerning capacity products, hydrogen transport tariffs, and balancing arrangements, could have direct impact on the operation of the Bramming–Veerst corridor. The market model offered by Energinet involves features such as capacity booking, nomination process, balancing obligations, and linepack flexibility utilization, whereas the final versions of market procedures should still be approved (Energinet, 2024, 2025). If capacity allocation and tariff schemes involve a large volume of firm capacity with considerable imbalance and linepack flexibility opportunities for shippers, the system will require being designed to deal with large short-term discrepancies in hydrogen injections and withdrawals. Consequently, there could be larger pressure swings at the Bramming inlet, up to the limits of 50–90 barg operating envelope and additional loading of the Mainline Regulator Station at Veerst. Also, this may result in a limited number of opportunities for scheduled shutdowns and maintenance work at line valve stations. Thus, the Bramming–Veerst corridor could work under smaller margin of pressure and flow which increases risks of pressure violations, curtailments, and other operational issues at inlet and pressure-regulation stations (Energinet, 2025).

On the other hand, a conservative approach regarding capacity products and balancing rules, such as smaller allowed imbalances and volume of firm capacity, would ensure that there is enough technical margin for the proper operation of the system. Nevertheless, it could restrict flexibility of shippers and negatively impact their ability to adjust to changing conditions regarding hydrogen production and demand and increase their effective hydrogen transport costs.

Capacity-product design affects maintenance and operational flexibility

The structure of capacity products can also affect when and how technical assets can be maintained. Energinet expects to offer long-term and shorter-term capacity products, including firm capacity, while capacity allocation and system operation must remain compatible with technical capacity and balancing requirements (Energinet, 2024, 2025). A market model focused mainly on long-term firm export capacity, particularly when combined with a strict “use-it-or-lose-it” principle, may leave few periods in which pipeline sections can be isolated or pressure can be reduced without affecting contracted transport. In such circumstances, line valve stations or the Mainline Regulator Station at Veerst may need to be operated during periods of higher flow or under greater time pressure. This can increase the risk of operational errors, such as incorrect valve sequencing, rapid pressure changes, or unwanted pressure transients in adjacent pipeline sections.

Alternatively, capacity products could include planned maintenance windows or periods of reduced availability. This would give Energinet more opportunity to carry out sectionalizing, depressurization, inspections, and maintenance under more stable conditions. The trade-off is that shippers may perceive these arrangements as reduced service availability. This example illustrates how a commercial decision about product design can influence the practical ability to operate and maintain technical assets safely. The connection between product design and maintenance scheduling is an analytical interpretation of the interaction between capacity commitments and the operational requirements of DHB1 assets (Energinet, 2024, 2025).

Technical constraints can require changes in market design

The relationship also works in the opposite direction: technical experience may require Energinet to adjust the market and regulatory framework. The proposed DHB1 balancing model depends on available linepack flexibility, nominated flows, and operating limits, while the final configuration of the backbone, connection conditions, and several market methodologies remain subject to further development and regulatory approval (Energinet, 2024, 2025). If early operation shows that maintaining the pressure limits at Bramming or Veerst is more difficult than expected, for example, because hydrogen injections are more variable than anticipated or available linepack flexibility is lower than planned, Energinet may need to reduce the amount of firm capacity offered to the market. It may also need to revise the balance between long-term and short-term capacity products or reserve a larger share of linepack for operational security rather than making it available for balancing.

Such adjustments would affect the capacity-allocation and tariff methodology and could require a revised submission to the Danish Utility Regulator, potentially followed by market consultation. Similarly, if the SCADA system at Bramming cannot reliably support highly frequent balancing actions, such as short re-nomination lead times or frequent imbalance adjustments, Energinet may need to use longer nomination lead times, allow wider imbalance tolerances, or simplify the balancing model. In this way, limitations in pressure management, linepack behavior, or control-system performance can directly reshape the rules that apply to shippers and the methods subject to regulatory approval.

2.2. Cluster 2: Cross-Border Export

2.2.1. Interfaces included in the cluster

This cluster studies the interaction between the organizational arrangements required for hydrogen export from Denmark to Germany and the technical infrastructure that enables pressure regulation, metering, quality control, and physical delivery at the border.

It includes two organizational interfaces. The first is the relationship between **Energinet and Gasunie Deutschland**, through which the two coordinate the Danish–German hydrogen interconnection, including capacity arrangements, operating conditions, and project development. The second is the relationship between **Energinet and the Danish Utility Regulator (DUR)**, through which Energinet submits tariff, capacity-allocation, balancing, and other market methodologies for approval. These arrangements affect the commercial conditions for cross-border export capacity (Energinet, 2024, 2025).

The cluster includes two technical interfaces. The first is the interface between the **new Bramming–Veerst pipeline and the Mainline Regulator Station (MRS) at Veerst**, where pressure and flow are regulated before hydrogen enters the repurposed pipeline toward Frøslev, Padborg, and Germany. The second is the interface between the **Padborg Mainline Metering Station (MMS) and the German Hyperlink 3** system at the Ellund interconnection point, where hydrogen flow and quality are measured, and pressure and flow are regulated before delivery into the German system (Energinet, 2025).

Together, these interfaces represent the part of DHB1 where cross-border governance, regulatory approval, pressure control, metering, and hydrogen-quality requirements meet.

2.2.2. Rationale for cluster 2

The interfaces were grouped because they jointly enable hydrogen to be exported safely, reliably, and in accordance with Danish and German market and technical requirements.

The cluster was constructed using the IAT by selecting interfaces connected to the Danish–German export route and to the organizations responsible for its market, regulatory, and operational arrangements.

The IAT shows that these interfaces are connected through several types of dependency. First, there are physical dependencies: pressure, flow, and hydrogen quality must remain compatible with the operating limits of the downstream Danish pipeline and the requirements at the German interconnection. Second, there are information dependencies: Energinet and Gasunie Deutschland need reliable metering, quality data, and operational information to confirm delivered volumes, settle capacity use, identify deviations, and coordinate responses to disturbances. Third, there are logical dependencies: capacity agreements, tariff methodologies, connection conditions, and regulatory approvals determine the conditions under which hydrogen can be transported and sold across the border.

The IAT risk, uncertainty, and vulnerability fields showed that the selected interfaces are exposed to related cross-border risks. These include uncertainty in regulatory approval, capacity and tariff arrangements, pressure and flow management, hydrogen quality compliance, metering accuracy, and operational data exchange. The cluster was therefore formed not simply because the interfaces are located along the same export route, but because their organizational, regulatory, informational, and

physical dependencies jointly determine whether DHB1 can deliver hydrogen to Germany safely, accurately, and under commercially viable conditions.

2.2.3. Cross-level vulnerabilities in this cluster

Binding commitments and synchronized development affect asset utilization

Cross-border hydrogen export requires the Danish and German parts of the corridor to be developed and commissioned in a coordinated manner. DHB1 depends on sufficient market commitments to support investment and state funding, while the realization of Hyperlink 3 also depends on reliable capacity requirements and commitments from future users. Energinet and Gasunie Deutschland have considered coordinated approaches to long-term capacity sales at the Danish–German interconnection point (Energinet, 2024, 2025).

A vulnerability may arise if commitments, permitting, financing, or construction progress differently on the two sides of the border. For example, the Danish backbone could become operational before sufficient downstream German capacity is available, or German demand could develop before Danish supply and export capacity are ready. In either case, the MRS Veerst and Padborg MMS could be underutilized or required to operate under lower and less predictable flow conditions than anticipated.

This example shows that commercial commitments and investment decisions affect whether the technical border assets can perform their intended export function. The stations may be physically complete, but their operational value depends on synchronized project delivery and market development in both countries.

National regulatory and tariff arrangements affect cross-border booking incentives

The Danish and German hydrogen systems are being developed under different national regulatory and economic arrangements. In Denmark, Energinet's tariff, capacity-allocation, and balancing methodologies are subject to approval by the Danish Utility Regulator. In Germany, the hydrogen core network is being developed under a separate framework, including ramp-up tariffs and cost-allocation arrangements intended to manage high initial infrastructure costs and limited early utilization (Energinet, 2024, 2025).

A vulnerability may arise if the combined cost, contractual conditions, or timing of Danish and German capacity products make cross-border transport difficult or unattractive for shippers to book. To export hydrogen from Denmark to Germany, shippers need compatible capacity arrangements on both sides of the interconnection. Even where technical capacity is available at Veerst and Padborg, it may remain underutilized if the combined tariff structures, booking conditions, or regulatory requirements create excessive cost or uncertainty.

This differs from the tariff issue in Cluster 1 because the concern is not only the Danish market framework. It is whether two national regulatory and cost-recovery systems create a commercially viable route for cross-border hydrogen transport.

Physical export limitations can reshape cross-border governance

DHB1 is designed primarily for physical southbound export from Denmark to Germany. Although commercial or balancing arrangements may allow a virtual northbound entry from Germany, this does not create physical reverse-flow capability under normal operation (Energinet, 2024, 2025).

This creates a vulnerability because a reduction or interruption of export cannot be offset by physically reversing the flow from Germany into Denmark. A disruption at either border station, or in the downstream German system, must therefore be managed on the Danish side through available linepack, curtailment of injections, or balancing actions. This makes the export corridor particularly dependent on reliable operation and coordinated incident procedures at the border.

Technical constraints at the border can therefore become organizational and regulatory vulnerabilities. They may reduce the volume of capacity that can be offered reliably, create uncertainty regarding delivered volumes or quality compliance, and require changes to the capacity-allocation or tariff methodologies submitted to the Danish Utility Regulator.

2.3. Cluster 3: Electricity–PtX Upstream

2.3.1. Interfaces included in the cluster

This cluster examines the interaction between electricity arrangements for Power-to-X (PtX) facilities and the technical interfaces through which electricity is converted into hydrogen and delivered to DHB1.

It includes the organizational relationship between **Energinet, as electricity transmission system operator, and PtX developers or operators**. This interface covers grid connection capacity, connection points, reinforcement needs, curtailment and ramping conditions, protection schemes, and communication requirements. These arrangements influence whether PtX facilities can access electricity and operate at the utilization levels assumed in their business cases.

The cluster includes two technical interfaces. The first is the interface between the **electricity transmission grid and the PtX plant**, including the electricity connection, transformers, protection systems, metering, and operational data exchange. The second is the interface between the **PtX hydrogen-production system and the producer connection pipeline leading to DHB1**, through which hydrogen must be delivered at the agreed pressure, temperature, flow, and quality conditions.

Together, these interfaces represent the upstream part of DHB1 where electricity-grid access is converted into hydrogen production and then into a controlled hydrogen supply for the backbone.

2.3.2. Rationale for cluster 3

The interfaces were grouped because they jointly enable hydrogen to be produced from electricity and delivered safely and reliably into DHB1. The cluster was constructed using the IAT by selecting interfaces connected to grid-connected PtX facilities and to the producer connection pipeline that transfers their hydrogen output to the backbone.

The IAT shows that these interfaces are linked through several types of dependency. First, there are physical dependencies: the electricity supply determines electrolyzer operation and hydrogen production, while the resulting hydrogen must meet the pressure, flow, temperature, and quality conditions required at the DHB1 entry point. Second, there are information and control dependencies: the electricity system operator and PtX operator require reliable metering, protection, alarms, and operational data to coordinate plant operation. Third, there are logical dependencies: connection agreements, reinforcement plans, curtailment rules, ramping requirements, and technical connection conditions determine how the PtX facility can operate.

The IAT risk, uncertainty, and vulnerability fields were used to confirm that the selected interfaces share connected upstream risks. These include uncertainty in grid-connection delivery and reinforcement, curtailment and ramping conditions, electricity-supply quality, electrolyzer performance, hydrogen-quality compliance, and the stability of hydrogen delivery into the producer connection pipeline.

The cluster was therefore formed not simply because the interfaces are physically adjacent. It was formed because electricity-grid decisions and PtX performance jointly determine whether the hydrogen volumes expected by DHB1 can be produced and delivered under stable operating conditions.

2.3.3. Cross-level vulnerabilities in this cluster

Grid-connection delivery and curtailment affect hydrogen supply

PtX projects depend on the timely delivery of grid connections, sufficient electrical capacity, and clear rules for curtailment and reinforcement. If connection agreements provide an expected connection capacity but reinforcement is delayed, or if curtailment conditions remain uncertain, PtX developers may postpone investment, reduce project scale, or operate the electrolyzer for fewer hours than planned.

At the grid-to-PtX interface, this can result in more frequent power reductions, outages, or start-up and shutdown cycles. These changes then affect the hydrogen side: lower or more variable electricity input produces lower or more variable hydrogen output to the producer connection pipeline. This may make it more difficult to maintain stable pressure and flow conditions at the DHB1 entry point.

This example shows that an organizational decision about grid access can affect not only the commercial viability of a PtX project but also the reliability of hydrogen supply available to DHB1. Energinet's hydrogen-balancing approach explicitly recognizes the importance of coordination between electricity-market conditions, hydrogen production, nominations, and hydrogen-system balance (Energinet, 2025).

Electricity-system flexibility can create hydrogen-side operating constraints

PtX facilities may be expected to respond to electricity-market signals or electricity-system needs by changing electricity consumption. This flexibility can support the power system, but rapid reductions or increases in electrical input may require the electrolyzer to ramp hydrogen production quickly.

If ramping requirements, protection schemes, or curtailment signals do not adequately reflect the operating limits of the PtX plant and its downstream hydrogen equipment, rapid electricity changes can create unstable hydrogen flow at the producer connection pipeline. This may increase the risk of pressure fluctuations, compressor trips, off-specification hydrogen, or delayed identification of abnormal conditions.

The vulnerability is therefore not that PtX flexibility is inherently problematic. It arises when the electricity-system operating requirements and the hydrogen-system requirements are not aligned. Connection agreements and operational procedures need to define ramping, communication, and protection arrangements that allow the PtX facility to support the electricity system without creating unacceptable disturbances for DHB1.

Technical performance can reshape connection conditions and supply expectations

Technical performance at the PtX facility could require organizational changes to the arrangements governing its grid connection and hydrogen delivery to DHB1.

Repeated voltage disturbances, electrolyzer trips, compressor failures, or hydrogen-quality deviations could reduce hydrogen output or create unstable pressure and flow in the producer connection pipeline. Energinet and the PtX operator may then need to revise connection conditions, protection settings, communication procedures, or permissible ramping rates.

A related vulnerability arises if Energinet's and the PtX operator's safety and control arrangements are not sufficiently aligned. For example, an emergency shutdown at the PtX plant may rapidly stop hydrogen production, while the connection pipeline and DHB1 entry station require a controlled reduction of flow and pressure. Unclear responsibilities for alarms, isolation, off-specification

hydrogen, or incident response could delay the management of an abnormal condition. Such operational procedures, including the handling of off-specification incidents and data exchange, are still being developed for DHB1 connections (Energinet, 2025).

Repeated underperformance can also affect wider planning assumptions. If PtX facilities deliver lower volumes or lower availability than expected, Energinet may need to reassess expected hydrogen supply, the use of entry capacity, and the need for future backbone expansion. Technical problems at the upstream interface can therefore become organizational vulnerabilities by affecting project financing, investment decisions, and confidence in the supply assumptions underpinning DHB1.

2.4. Cluster 4: Producer Entry

2.4.1. Interfaces included in the cluster

This cluster examines the point at which direct hydrogen producers connect to Danish Hydrogen Backbone 1 (DHB1) and inject hydrogen into the transport system. It focuses on the interaction between the agreements governing producer access and the technical interfaces that control hydrogen quality, pressure, flow, monitoring, and safety at the entry point.

It includes the organizational interface between **Energinet, as the hydrogen transmission network operator, and direct producers or consumers at injection/extraction (I/E) stations**. This interface covers connection agreements, responsibilities, hydrogen-quality requirements, pressure and temperature limits, ramping and nomination rules, curtailment arrangements, monitoring, and incident procedures.

The cluster includes two technical interfaces. The first is the interface between the **PtX plant or hydrogen-production system and the producer connection pipeline**, where hydrogen is conditioned, compressed, monitored, and transferred toward DHB1. The second is the interface between the **DHB1 I/E station and the backbone pipeline**, where hydrogen is metered, checked for quality, pressure-regulated, and injected into the transmission system. Energinet is expected to validate flow and hydrogen quality at I/E stations, while the detailed procedures for data exchange and off-specification incidents are to be defined in connection agreements (Energinet, 2025).

Together, these interfaces represent the gateway through which new hydrogen producers gain access to DHB1.

2.4.2. Rationale for cluster 4

The interfaces were grouped because they jointly enable producers to inject hydrogen into DHB1 safely and reliably. The cluster was constructed using the IAT by selecting the interfaces related to producer connection agreements, producer connection pipelines, and I/E stations.

The IAT shows that these interfaces are connected through several types of dependency. First, there are physical dependencies: hydrogen delivered from the producer must meet the pressure, flow, temperature, and quality conditions required for safe backbone operation. Second, there are information and control dependencies: Energinet and producers need reliable metering, quality data, alarms, and operational communication to identify and respond to abnormal conditions. Third, there are logical dependencies: connection agreements, operating limits, ramping rules, curtailment arrangements, and incident responsibilities determine how producers can use the connection.

The IAT risk, uncertainty, and vulnerability fields showed that the selected interfaces are exposed to related entry-point risks and uncertainties. These include uncertainty in connection conditions and producer operating profiles, off-specification hydrogen, pressure and flow deviations, start-up and shutdown transients, monitoring failures, and disputes over responsibilities or access conditions.

The cluster was therefore formed not simply because the interfaces are located at the same connection point, but because organizational access rules and technical entry conditions jointly determine whether new producers can connect to and operate within DHB1 safely and effectively.

2.4.3. Cross-level vulnerabilities in this cluster

Responsibility, data, and safety coordination affect producer access

Producer entry depends not only on meeting hydrogen-quality and pressure requirements, but also on clear coordination between Energinet and the producer. The connection agreement must establish who is responsible for measurement, monitoring, alarms, isolation, data sharing, and the response to off-specification hydrogen or abnormal operating conditions.

A vulnerability may arise if Energinet's and the producer's monitoring, safety, or incident-response arrangements are not sufficiently aligned. For example, a producer-side trip or emergency shutdown may rapidly reduce hydrogen flow, while the I/E station and DHB1 require a controlled reduction in pressure and flow. Likewise, unclear alarm responsibilities or delayed data exchange could prevent abnormal hydrogen quality or pressure conditions from being identified and managed before they affect the backbone.

This could require additional sensors, more detailed alarm thresholds, clearer isolation procedures, or revised responsibilities in the connection agreement. Energinet expects the connection agreement to define procedures for off-specification incidents, operational data exchange, and related interactions between Energinet and connected producers (Energinet, 2025).

Variable producer operation affects backbone stability and connection conditions

Hydrogen production from PtX facilities may vary because of electricity prices, electricity-system curtailment, electrolyzer operation, or equipment failures. If a producer changes its output rapidly, the resulting hydrogen-flow changes can create pressure and flow transients in the producer connection pipeline and at the I/E station.

Connection conditions must therefore balance producer flexibility with the backbone's need for stable operation. Permitting fast ramping may allow producers to respond to electricity-market signals, but it can increase the risk of compressor trips, pressure excursions, and unstable flow at the DHB1 entry point. More conservative ramping limits can reduce this technical risk but may reduce the producer's operational flexibility and project value.

If repeated pressure, flow, or quality problems occur at a connection point, Energinet may need to revise ramp-rate limits, curtailment conditions, monitoring requirements, or the volume of capacity that can be used reliably. Technical performance at the entry point can therefore become an organizational vulnerability by affecting producer access conditions, future connection costs, and confidence in the hydrogen supply expected by DHB1.

2.5. Cluster 5: Control and Coordination

2.5.1. Interfaces included in the cluster

This cluster examines the control and coordination arrangements that enable DHB1 to operate as one integrated system. It focuses on the relationship between operational information (such as nominations, metering, pressure, flow, linepack, and alarms) and the organizational decisions required to balance the system, coordinate cross-border operation, and apply approved market rules.

It includes three organizational interfaces. The first is the relationship between **Energinet and shippers**, which covers nominations, balancing obligations, system information, and responses to imbalances. The second is the relationship between **Energinet and Gasunie Deutschland**, through which the two transmission-system operators coordinate operation at the Danish-German interconnection. The third is the relationship between **Energinet and the Danish Utility Regulator (DUR)**, which concerns the approval and oversight of methodologies for balancing, capacity allocation, and tariffs.

The cluster includes three technical interfaces with essential monitoring, metering, pressure-regulation, or control functions. The first is the **Bramming PLR/main valve station-Energinet SCADA interface**, which provides pressure, flow, valve-status, and alarm information, as well as remote-control capability. The second is the interface between the **new Bramming-Veerst pipeline and the Mainline Regulator Station (MRS) at Veerst**, where pressure and flow are regulated between the new and repurposed pipeline sections. The third is the interface between the **Padborg Mainline Metering Station (MMS) and the German Hyperlink 3 system at the Ellund interconnection point**, which provides flow and quality measurement, pressure control, and operational data at the border.

Together, these interfaces represent the coordination layer through which DHB1's physical condition is monitored, interpreted, and translated into operational, commercial, and regulatory decisions.

2.5.2. Rationale for cluster 5

The cluster was constructed using the IAT by selecting interfaces whose main role is to collect operational information, control hydrogen flows, coordinate actions among system actors, or establish the rules through which operational decisions are made. The technical interfaces provide system visibility and control at the inlet, at the pressure transition in Veerst, and at the Danish–German border. The organizational interfaces determine how this information is used for nominations, balancing, cross-border coordination, and regulatory compliance.

The IAT shows that these interfaces are connected through several types of dependency. First, there are information and control dependencies: SCADA, telemetry, flow measurement, quality data, alarms, and operational communication provide the information required to monitor the system. Second, there are physical dependencies: pressure and flow conditions at Bramming, Veerst, and Padborg must remain within safe operating limits. Third, there are logical dependencies: nomination procedures, balancing rules, capacity arrangements, incident responsibilities, and approved methodologies determine how actors interpret information and respond to deviations.

The IAT risk, uncertainty, and vulnerability fields showed that the selected interfaces are exposed to related coordination risks. These include delayed or inaccurate telemetry, SCADA outages,

metering discrepancies, pressure-control failures, uncertainty in nomination and balancing procedures, and unclear cross-border incident responsibilities.

The cluster was therefore formed because reliable system operation depends not only on individual assets functioning correctly, but also on the ability of Energinet, shippers, Gasunie Deutschland, and DUR to act on a common and reliable understanding of the system's condition.

2.5.3. Cross-level vulnerabilities in this cluster

Data quality affects balancing, settlement, and operational decisions

DHB1's balancing model depends on information about nominations, actual flows, linepack flexibility, and the balance position of individual shippers and the system. Energinet expects to provide information on system linepack flexibility, individual shipper flexibility, and system balance in real time or as close to real time as possible (Energinet, 2025).

A vulnerability may arise if SCADA signals at Bramming, pressure and flow data from Veerst, or metering data at Padborg are delayed, inaccurate, or unavailable. Energinet may then be unable to distinguish clearly between a shipper imbalance, a technical fault, a measurement problem, or a cross-border operating constraint. This can require more conservative operational decisions, such as reserving additional linepack, curtailing flows, or applying balancing actions before the cause of the deviation is fully confirmed.

The consequences extend beyond technical operation. Incomplete or inconsistent data may create uncertainty about shipper imbalance charges, capacity use, or the allocation of balancing costs. A technical data-quality problem can therefore become an organizational and commercial vulnerability because it affects the basis on which responsibilities and costs are assigned.

Incident coordination depends on shared control and response procedures

A pressure-control problem at Veerst, a SCADA failure at Bramming, or a metering discrepancy at Padborg may require rapid coordination between Energinet, shippers, and Gasunie Deutschland. The physical system may need immediate intervention, while shippers may need to adjust nominations or flows and the German system operator may need to respond at the interconnection point.

A vulnerability can arise if actors do not share clear procedures for validating data, communicating incidents, applying emergency curtailment, or deciding when manual operation is required. For example, if the Danish and German operators receive inconsistent metering data or interpret an alarm differently, they may disagree about the cause of a deviation or the need to restrict export capacity.

This can delay corrective action and create disputes concerning capacity availability, balancing responsibilities, or compliance with operating arrangements. Technical failures in monitoring, control, or metering therefore become governance vulnerabilities when the procedures for interpreting and acting on technical information are unclear or insufficiently coordinated.

3. Questions for Expert Validation

The following questions are intended to support discussion and validation of the preliminary cluster analysis. You are welcome to comment on all five clusters or to focus only on the cluster or clusters most relevant to your experience and expertise. Please feel free to leave any question unanswered if it falls outside your area of knowledge or if you do not have sufficient information to comment.

3.1 Cluster reflection

- Which cluster or clusters are most relevant to your experience?
- Do the selected cluster(s) capture the most important elements and relationships relevant to this area of DHB1? If not, what do you think is missing or should be reconsidered?
- Which cluster do you consider most critical for DHB1, and why?
- Based on your experience with DHB1 or comparable projects, are there concrete situations that illustrate, support, or challenge the situations and interactions described in the selected cluster(s)?

3.2 Uncertainty and vulnerability

- Do the situations and potential problems described in the selected cluster(s) seem realistic in practice? Is anything important missing or described differently from how you would expect it to work?
- For the cluster(s) most relevant to you, which uncertainties would be most difficult to manage in practice?

3.3 Mitigation measures

- What measures could most effectively reduce the risks or weaknesses identified in the cluster(s) most relevant to you?
- Are there technical, operational, contractual, governance, or regulatory changes that could improve resilience?

F

Development of the Cross-Level Clusters

This appendix documents how the preliminary cluster groupings were revised during the analysis and expert review. Table F.1 identifies the groupings retained or merged and the interfaces added, removed, or redefined. Interface identifiers refer to the final IAT records in Appendix A.

Table F.1: Changes from the preliminary cluster groupings to the final analysis.

Preliminary grouping	**Decision and changes to the interfaces included**
Cluster 1: Backbone Access, Tariffs, and Balancing	Retained as final Cluster 1.
	Added T3 (DHB1 mainline–I/E station), T5 (MRS Veerst–converted Veerst–Frøslev pipeline), and T10 (converted Veerst–Frøslev pipeline–Padborg MMS).
	Removed the Bramming PLR/main valve station–new Bramming–Veerst pipeline interface (T1), the pipeline–line-valve-station interface (T2), and the preliminary Bramming PLR–SCADA interface from this cluster.
	Retained T4 (new Bramming–Veerst pipeline–MRS Veerst), O1 (Energinet–shippers), and O4 (Energinet–Danish Utility Regulator). The revised grouping connects market access and balancing arrangements to hydrogen entry, pressure regulation, and onward transport.

Table F.1: Changes from the preliminary cluster groupings to the final analysis (continued).

Preliminary grouping	Decision and changes to the interfaces included
Cluster 2: Cross-Border Export	Retained as final Cluster 2. Added T5 (MRS Veerst–converted Veerst–Frøslev pipeline) and O1 (Energinet–shippers). Replaced the preliminary Padborg MMS–German Hyperlink 3 technical interface with T10 (converted Veerst–Frøslev pipeline–Padborg MMS), bringing the technical assessment within the selected Danish boundary. Coordination with the German system remains covered through O3 (Energinet–Gasunie Deutschland). Retained T4 (new Bramming–Veerst pipeline–MRS Veerst), O3, and O4 (Energinet–Danish Utility Regulator).
Cluster 3: Electricity–PtX Upstream; and Cluster 4: Producer Entry	Merged into final Cluster 3: Electricity Supply, PtX Production, and Producer Entry. Their vulnerability mechanisms were closely related, and combining them made the links between electricity availability, production, and producer entry clearer. Retained T8 (electricity transmission grid–PtX facility) and O5 (Energinet as electricity TSO–PtX developers or operators) from preliminary Cluster 3; T3 (DHB1 mainline–I/E station) and O2 (Energinet as hydrogen network operator–direct producers) from preliminary Cluster 4; and T7 (PtX hydrogen-production system–producer connection pipeline), which appeared in both preliminary groupings. Added T9 (producer connection pipeline–DHB1 I/E station), making the connection between producer-side infrastructure and the entry station explicit. No interface from either preliminary grouping was removed.
Cluster 5: Control and Coordination	Retained as final Cluster 4: Operational Information, Control, and Coordination. Added T1 (Bramming PLR/main valve station–new Bramming–Veerst pipeline), T5 (MRS Veerst–converted Veerst–Frøslev pipeline), and T6 (DHB1 I/E stations–Energinet SCADA). Removed the preliminary Bramming PLR–SCADA interface. Replaced the preliminary Padborg MMS–German Hyperlink 3 technical interface with T10 (converted Veerst–Frøslev pipeline–Padborg MMS). Retained T4 (new Bramming–Veerst pipeline–MRS Veerst), O1 (Energinet–shippers), O3 (Energinet–Gasunie Deutschland), and O4 (Energinet–Danish Utility Regulator). The revised grouping connects operational information and organizational responses to the physical interfaces requiring monitoring and control.