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Incorporating Safety-II in future gas systems

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A B S T R A C T

This article studies safety management in future gas systems. It is structured around the compatibility of its technological and institutional coordination. We identify how the current mode of safety management is not in harmony with increasingly complex technological and institutional arrangements, and combine safety science with institutional analysis to improve safety management. For our case study of biogas quality monitoring in the Netherlands, we offer structured recommendations for the reallocation of monitoring and enforcement mechanisms based on Safety-II. This article provides insights for users of gas systems and other infrastructures alike, and it offers safety scholars an approach to safety management that incorporates a novel focus on institutions.

1. Introduction

The rapidly changing features of traditional energy systems poses novel challenges for their safety management. High profile disasters, such as the 2015 cyber-attack on Ukraine's power infrastructure and the 2021 Texas winter blackout, illustrate these challenges and point towards new areas of concern. The former was only possible as a consequence of increased digitalization of energy systems, whereas the latter resulted from a high system vulnerability induced by more variety in power generation and a regulatory structure that failed to incentivize back-up gas supply and generation (Busby et al., 2021; Sullivan & Kamensky, 2017). Safety management in these systems must account for increasing digitalization and interconnectivity, new hazards, and changing existing ones (Riemersma et al., 2020b). The fact that energy systems are becoming more complex and institutionally fragmented further complicates this (Glachant, 2012; Goldthau, 2014; Riemersma et al., 2020b). This paper focuses on safety management in energy systems and takes the changing gas infrastructure as an example.

New types of gas are not always compatible with existing infrastructure. Technologies facilitating their production and transport make systems more complex while operational and safety responsibilities are allocated over a growing and increasingly heterogeneous group of actors (Riemersma et al., 2020b). To illustrate, the production of biogas is often small-scale and geographically dispersed while consumption often takes place relatively close to the locations of production. In such local grids, it becomes more challenging to manage infrastructure functions such as gas quality control, (bi-directional) transport, storage, and grid balancing. Institutions (rules and norms) have developed in tandem with technological developments to manage safety in traditional natural gas infrastructure (Riemersma et al., 2020a). Now, safety management involves defining, monitoring and enforcing rules for the established gas industry, as well as a for the local dairy farmer—let's call him Farmer John—who has recently started producing biogas from the manure of his cows. Natural gas supplied by the industry and biogas produced by Farmer John have comparable hazard profiles: improper production or combustion may result in possibly fatal accidents from fire, explosion or poisoning (Riemersma et al., 2020b). But at the same time, the established gas industry and Farmer John have different levels of expertise and capabilities to mitigate safety concerns, and grid operators receiving biogas into their natural gas systems may have little previous experience with important safety tasks (Riemersma et al., 2020b). These observations inform the central question of this paper: How can safety management incorporate the fundamentally changing interrelationship between technological and institutional characteristics for future gas systems?

Our study of safety management in gas systems involves the academic disciplines of Safety Science and Institutional Economics. The study of Safety Science is concerned with understanding accident processes (Swuste et al., 2020). To this end, methods are developed for the identification, mitigation and prevention of safety hazards (Hollnagel, 2012; Leveson, 2011). We showed in previous papers how gas systems are undergoing major changes (Riemersma et al., 2020a), and how their

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Abbreviations: ACM, Authority Consumers and Markets; DSO, Distribution System Operator; GTS, Gasunie Transport Services; LNG, Liquefied Natural Gas; SODM, *Staatstoezicht op de Mijnen* (State Supervision of Mines); TSO, Transmission System Operator.

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changing features call for a systemic view on safety—including the use of different hazard analysis techniques (Riemersma et al., 2020b). We continue this line of research by applying a Safety-II lens to Netherlands gas systems. A Safety-II approach advocates learning from everyday behavior over learning from incidental accidents, and promotes adaptability in systems as a way to manage increasing complexity (Provan et al., 2020; Rasmussen, 1997). We are interested in exploring how safety management in gas systems can be designed from a Safety-II perspective. The implementation of a Safety-II approach has mostly focused on the organization (Moorkamp et al., 2014; Provan et al., 2020), while a few sector-wide examples exist (Leistikow & Bal, 2020; Papadimitriou et al., 2022). We add a unique institutional focus to this body of literature which, to the best of our knowledge, does not yet exist. We assess safety management by means of a line of research that studies the joint impact of institutional and technological developments on managing infrastructures (Finger et al., 2005; Künneke et al., 2021; Ménard, 2014). This paper thus also continues in a tradition of institutional economists that have focused on economic coordination (Glachant, 2012; Groenewegen & De Jong, 2008); different types of infrastructure regulation (Correljé, 2005; Finger et al., 2005; Libecap, 2008; Ménard, 2017); or how public values are maintained in liberalized infrastructures (Correljé et al., 2015; Steenhuizen & van Eeten, 2008; Veeneman et al., 2009).

The structure of this paper is as follows. Section 2 provides an overview of safety concerns in future gas systems; Section 3 introduces two modes of Safety Management; Section 4 unfolds the methodology, including an introduction to the Alignment Framework; Section 5 prepares the analysis by bridging the Alignment Framework and Safety-II; Section 6 introduces the Netherlands Gas system as a case study, and studies safety in it; Section 7 discusses; Section 8 concludes.

2. Safety in future gas systems

Natural gas has specific physical properties. Combustion appliances, such as stoves, turbines or boilers, are designed to safely and efficiently use gas with specific proportions of methane, nitrogen, carbon dioxide or other properties or characteristics (Riemersma et al., 2020a; Schweitzer & Cagnon, 2011). Generally, in a particular geographical region, the composition of gas that can be safely used is historically determined, as a consequence of the origin of the gas supplied initially and the associated technical specifications of the appliances in place. As a result, existing infrastructure is important for determining the quality specifications of any gas that might substitute the gas that it was designed for.

Existing gas infrastructure may need to accommodate different types of gasses for a variety of reasons. The rapid decline in gas production in the Netherlands, for example, forces the country itself as well as neighboring Germany and Belgium to find alternatives (Riemersma et al., 2020a). These alternatives could be natural gas provided by pipeline (i.e. from Norway or the UK) or by ship (i.e. from the Middle East or the United States), but also a variety of renewable gasses. We focus here on the implications of biogas usage, the most prominent renewable gas that is currently compatible with existing natural gas infrastructure. Biogas can be produced from a wide range of sources including organic waste and manure. To become interoperable with the existing natural gas infrastructure, it has to be upgraded. This typically involves lowering its water content, and (partially) removing substances that are harmful to humans and equipment, such as sulfur, hydrogen sulfide or carbon monoxide (ibid.). Both of the latter compounds are highly hazardous (KIWA, 2007), and especially carbon monoxide is a leading cause of gas-related accidents (Onderzoeksraad voor Veiligheid, 2015). Even after upgrading, biogas may contain potentially harmful components. Producing biogas from citrus peels, for example, yields limonene, a volatile organic compound (VOC) with very distinct citrus smell. The citrus smell has the capacity to overpower the mercaptan smell traditionally associated with natural gas, thereby bypassing one of the most distinguishable safety features of gas—its smell (Tempelman & Butenko, 2013). In the Netherlands in 2021, there were two recorded instances of biogas properties masking gas smell (Netbeheer Nederland, 2022b).

The production characteristics of biogas differ significantly from those of natural gas. A shift towards more small-scale and decentralized production uproots both the technological system that was designed for large-scale and centralized natural gas production, as well as the set of rules and regulations that guided the actions and behavior of the few actors involved with gas production, trade and transport (Riemersma et al., 2020b). Even if future safety hazards are adequately identified, appropriate safety measures must be allocated, monitored and enforced. Farmer John, who turns organic waste into biogas, requires different safety measures than a gas company operating a major offshore natural gas field. Regulation is likely necessary to ensure that the gas produced by Farmer John and the gas company is compatible with the existing gas infrastructure; but interaction of both types of gas producers with grid operators, regulators, and legislators is likely very different. The discipline of Safety Science provides insights on how to manage safety in systems like this, that are turning increasingly complex.

3. Managing safety

3.1. Two modes of safety management

The discipline of Safety Science distinguishes at least two modes of safety management. Following the seminal book of Erik Hollnagel (2014), these can be summarized as Safety-I and Safety-II. Safety-I rests on the premise that a system is safe when there is an absence of accidents and unacceptable risks (Aven, 2022; Hollnagel et al., 2015). Safety protocols are designed to define roles and procedures such that their successful execution prevents accidents and limits risk, thereby ensuring safety. Failures and errors in equipment or personnel operations cause accidents. Safety management involves taking lessons from these accidents so that they may be prevented in the future. This mode of safety management is assisted by risk assessment tools that estimate the likelihood and consequences of accidents. Safety practices then can be channeled towards reducing the likelihood of accidents or mitigating their impact. It relies on compliance and a continuous upgrading of safety controls by incorporating cumulative knowledge of situations where system behavior is non-compliant (Hollnagel, 2014; Provan et al., 2020). In other words, it is informed by monitored deviations from expected behavior. These observations are then collected by a central actor, such as a regulator or a management unit, after which safety management can be adjusted to mitigate the observed deviation in the future. This mode of safety management is particularly effective in systems where knowledge about system behavior is abundant, and past performance provides a good indication of current and future behavior. These systems are generally linear and simple or, when they are more complicated, decomposable in non-interacting units (Hollnagel, 2014; Provan et al., 2020).

Safety-II perceives safety as a system's "ability to succeed under varying conditions" (Hollnagel, 2014, p. 137). It is designed for systems that are complex and non-linear. It is difficult to predict behavior in these systems as safety hazards may follow from unexpected interactions between linked system components. Safety-II posits that it might not be possible to establish root causes for all hazards and accidents. They might be hidden (like in software) or spring from a combination of latent conditions and extreme events (like the Texas Blackout). In other words, accident causality may be *emergent* from unexpected system interactions (Leveson, 2011). Because of the inability to comprehend full system behavior and the associated difficulty to identify and quantify all risks and possible accidents, Safety-II stresses the importance of looking at *what goes right* instead of *what goes wrong*. It puts high frequency activities center stage, and focuses on the conditions that make them *generally* safe. In theory, this knowledge helps to understand under what conditions systems meet expectations, and can be employed to further bolster these conditions. This mode of safety management calls for a shift from centrally monitored compliance of safety controls, to more decentral operating decision centers that adapt existing protocols to local conditions (Leistikow & Bal, 2020; Oedewald & Gotcheva, 2015; Reiman et al., 2015). This decentral mode of safety management marries explicit knowledge (from a ruleset) and tacit knowledge (from experience). Additionally, Safety-II relies on risk assessment tools that identify hazardous system states rather than root causes for accidents (Provan et al., 2020). Table 1 summarizes and compares the key features of both modes of safety management.

Gas systems increasingly reflect complex systems due to growing small-scale production and digitization (Riemersma et al., 2020b). In earlier research, we showed how new developments in gas systems, and energy systems more broadly, require risk assessment methods that are rooted in a Safety-II approach. We now extend this line of argument by assessing the institutional incorporation of a changing style of safety management. Few studies exist that apply the concept of Safety-II to changing industries or infrastructures. Exceptions include studies on road safety (Papadimitriou et al., 2022) and health care (Bentley et al., 2021; Leistikow & Bal, 2020), but they do not focus on changing roles and responsibilities with regards to rules for safety. In other words, there is no structural approach for assessing institutional features of infrastructure systems with respect to Safety-II.

3.2. *Towards an institutional approach to safety management*

We apply the concept of *Alignment* between technology and institutions to assess safety management. This concept rests on the assumption that for fundamental, or *critical*, infrastructure functions to perform as expected, technological and institutional coordination of these functions must be compatible or, in other words, *aligned* (Künneke et al., 2021). In this sense, safety is considered a critical function that needs to be maintained by interrelated technological and institutional arrangements. In this context institutions are perceived as a set of rules and norms that guide human interaction (North, 1990). The Alignment Framework by Künneke, Ménard and Groenewegen builds on micro-economics, institutional economics and Socio-technical Systems Theory with a focus on the *interdependence* between technology and institutions (Finger et al., 2005; Hughes, 1987; Künneke et al., 2010; Ménard, 2014).[1] Much like Safety-II, this approach follows a systemic approach to (infrastructure) performance that goes beyond a component focus. It includes a focus on the overall technological architecture of a system, and the way in which it is implemented with respect to various environmental conditions. It recognizes the importance of rules and norms as institutions that manage infrastructure performance (including safety), and adds an explicit focus on the interpretation of these rules and the way in which they are executed in their specific local and temporal context.

Fundamental to the Alignment Framework are its three layers of analysis. The three scales of alignment comprise *Structure*, *Governance*, and *Transactions*. Each of these layers looks at the compatibility of institutional and technological coordination at a different resolution. Table 2 provides an overview. Section 4 introduces the Methodology. Section 5 introduces the layers and their constitutive components as building blocks for safety management. The three layers of alignment will be introduced in sections 5.1. through 5.3; Section 5.4. introduces the variables that determine alignment.

Table 1
Comparison and Summary of two modes of safety management (adapted from Hollnagel, 2014; Leistikow & Bal, 2020).

	Safety-I	Safety-II
Definition of safety	Absence of accidents	Ability to perform system functions under varying conditions
Causality	Component failure or error	Emergent from system interactions
Safety Management	Reactive, based on past performance	Proactive, based on readiness to adapt to new conditions
Risk Assessment	Identify high probability and severe outcome accidents	Identify system states that lead to hazardous situations
Models and system characterization	Simple and/or decomposable	Complex and non-linear

4. Methodology

This study builds on earlier work in our project on safety management in gas transport systems, with an empirical focus on the developments in the Netherlands. The first study identified trends in Netherlands gas systems, and examined their implications for safety (Riemersma et al., 2020a). It showed how the increasing decentralization of gas production created safety hazards related to the increasing variety in gas qualities. The second study compared analytic and systemic risk assessment methods, and found types of safety hazards associated with new gas systems (Riemersma et al., 2020b). Data from both cited papers provided directions for this research. The first provided knowledge of and historical context for the Netherlands gas system; the second provided a systematic literature review on the use of analytic and systemic hazard analysis techniques in the Safety Science literature as well as practical knowledge on the use of hazard analysis techniques in Netherlands gas systems.

The aim of this study is to improve the applicability of the Safety-II concept to the coordination of complex socio-technical systems. It bridges two disciplines through synthesis by doing so (Sovacool et al., 2018). Like studies with a similar approach (Menard et al., 2021; Sovacool & Van de Graaf, 2018), this paper is structured along a conceptual framework. It uses the Alignment Framework because of its explicit focus on the interrelationship between technological and institutional arrangements. Our analysis is a qualitative case study that further draws information from peer-reviewed literature, industry and regulators' reporting and grey materials. Additionally, it uses materials gathered during earlier phases of this research project (Riemersma et al., 2020a; Riemersma et al., 2020b). The case study was selected because it displays both rapidly changing technological *and* institutional developments, and enables us to test the assumption that the joint application of the Alignment Framework and the concept of Safety-II yields the identification of detailed and targeted instances where safety management can be improved. In order to verify the relevance of the case study, overcome bias in study design, we corroborated initial findings by

Table 2
The Alignment Framework (Künneke et al., 2021).

Aligning Technology and Institutions		
Technological Dimension	**Modality of alignment**	**Institutional Dimension**
Technological Architecture	Structure	Macro-Institutions
Technological design	Governance	Meso-Institutions
Technical Operation	Transactions	Micro-institutions

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[1] Künneke *et al.* discuss how their approach differs from and complements these three strands of research in their 2021 book (Künneke et al., 2021, pp. 27–33).

two additional interviews with asset managers of grid operators conducted by the author in early 2021.[2] Both interviewees worked on the integration of renewable gasses in gas distribution networks in the Netherlands. These interviews confirmed variations in existing methods of monitoring and enforcing gas quality in the Netherlands, and relevant technological and institutional developments in Netherlands gas systems.

5. The building blocks of safety management in infrastructures

5.1. Structure

5.1.1. Technological Architecture

The Technological Architecture refers to generic technological features. Comprising basic nodes and links, it "stipulates the generic technological features, embedded in physical systems, necessary to provide the services expected form the network infrastructure at stake" (Künneke et al., 2021, p. 237). For gas infrastructures, these essentially involve production facilities, high pressure transmission infrastructure, medium- and low-pressure distribution infrastructure, storage capacity and combustion devices. The architecture supports basic functionalities that typically only change slowly over time (Faulconbridge & Ryan, 2014; Künneke et al., 2021). The primary functionality for the gas system is the provision of gas from imports and production to industries and households.

5.1.2. Macro-Institutions

Macro-Institutions refer to the "institutional layer within which "constitutive" norms and rules are established that delineate and structure the domain of possible transactions[3] necessary to provide the services expected from the network infrastructure at stake" (Künneke et al., 2021, p. 238). Legislative bodies such as the EU or national governments operate in the Macro-Institutional layer when they define rules for gas production, trading and transport. They stipulate what can and what cannot be done. It bears similarity to what is labelled the *institutional environment* by Oliver Williamson, laying out the rules of the game (Williamson, 1998). EU directives, for example, forbid actors involved with gas production and trading to be involved with gas transport and vice versa, while the gas transport infrastructure should be accessible on equal terms to all market parties that request access to it.

Legislative bodies in the macro-layer allocate rules and decision rights (Künneke et al., 2021; Ménard, 2017). Decision rights specify how different rules can be exercised, thereby providing the contours for their interpretation (Ménard, 2017). Fundamental rules such as those defined in the macro-layer evolve only gradually and typically reflect a set of shared beliefs and past policy choices. Informal institutions, such as traditions and norms, can also be influential in shaping rules and decision rights. For many infrastructures these include a widespread belief that governments and, by extension, publicly owned infrastructure providers, ought to protect a general level of safety (Frischmann, 2012; Künneke et al., 2021).

5.2. Governance

5.2.1. Technological design

The context within which the generic architecture is implemented is the area of Technological Design. This design "relates to the context-specific arrangement of technical and material components necessary, within a given generic architecture, to make up a network delivering services to a certain time and place" (Künneke et al., 2021, p. 85). Different designs may be suitable depending on technological choices from the past, and relevant temporal, spatial and regulatory conditions. The differing *Designs* for biogas quality monitoring in the Netherlands and Denmark provide an example. While both countries' traditional gas infrastructures have a comparable architecture, increasing biogas production has put both infrastructures on different trajectories. The Netherlands relies on small-scale and individual biogas quality monitoring whereas Denmark is accustomed to collective larger-scale gas quality upgrading and monitoring (Raven & Geels, 2010).

5.2.2. Meso-Institutions

Meso-Institutions translate, monitor and enforce rules defined in the macro-sphere (Künneke et al., 2021). These three fundamental functions are important in shaping the way in which rules coordinate daily operations. Examples of Meso-Institutions include regulatory agencies or public bureaus. Following Ménard, we distinguish four different categories of such coordinative devices. From most centralized to most decentralized, these include public bureaus, regulatory agencies, communities and markets (Ménard, 2017). The choice of device bears significant consequences for the procedures through which rules are implemented and, more specifically, the way in which infrastructures are managed. Public bureaus, for instance, issue directives themselves that specify the way in which rules must be implemented, monitored and enforced. Agencies may delegate some functions, for example the monitoring of gas quality, while maintaining authority of translation and enforcement; communities may determine the way in which rules are exercised by a process of negotiation and discussion among the most involved parties in a process of decentralization; and markets might leave the most efficient way in which rules are translated and implemented to market instruments such as auctions, relying on judicial authorities to settle disputes (Ménard, 2017).

5.3. Transactions

5.3.1. Technical operation

Technical Operation refers to "the operation of technical and material components necessary, within a given generic architecture, to make up a network delivering services specific to a certain time and space" (Künneke et al., 2021, p. 237). Within a given generic architecture and context-dependent design, the *Technical Operation* layer thus focuses on day-to-day infrastructure operation. Gas quality monitoring of renewable gasses illustrates a number of trade-offs in the daily technical operation of gas systems. For example, biogas quality might be monitored at different intervals. Based on the perceived risk associated with a particular production method or (type of) producer, grid operators might opt to monitor gas quality, for example, every five minutes or twice a day.

5.3.2. Micro-Institutions

Transactions are to "the transfer of rights to use goods and services across technologically separable activities" (Künneke et al., 2021, p. 63). *Micro-Institutions,* then, refer to the "organizational arrangements through which transactions are planned, implemented, and monitored (Künneke et al., 2021, p. 47). Examples of micro-institutional arrangements include contracts, like those between biogas producers and grid operators, as well as public–private partnerships, or vertically integrated firms (Künneke et al., 2021). In the context of gas provision, transactions are planned and executed by contracts in the market. Market forces dictate, at least to an extent, what conditions favor gas production in certain locations and times. Markets facilitate a process of price discovery until a price is reached where gas supply meets demand. Markets are less effective, however, in pricing in valuables that are hard to quantify, such as safety.

Alternatives to organizing transactions through market mechanisms include varying ways of government or community involvement. Strong local communities, for example, might effectively transact goods and services without (significant) government or market involvement (E. Ostrom, 1990, 2005), while transactions characterized by a high degree

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[2] on 26–01-2021 and 09–02-2021.

[3] Transactions are introduced in 5.3.

of uncertainty and complexity might benefit from centralized coordination (Williamson, 2010). Decentral and market-based instruments might effectively promote the aggregation and use of knowledge that is dispersed through large interconnected systems (Salter & Tarko, 2017). Different arrangements might be suitable for different technical designs.

5.4. *Modalities of Alignment*

Across all three layers, we can determine alignment by identifying three modalities of technological and institutional coordination related to safety management. These modalities are the centrality, adjustability and scope of coordination. Table 3 shows how each are typically associated with Safety I and II. Safety-I is centralized, closed, and monocentric, whereas Safety-II is perceived decentralized, open, and polycentric. We expect a more appropriate safety management, if the corresponding technological and institutional coordination arrangements are aligned. The next three paragraphs elaborate this in more detail.

5.4.1. *Centrality of coordination*

The centralization of coordination refers to the plurality of institutional and technological devices used for satisfying desired infrastructure functioning (Künneke et al., 2021). Starting with the *Technological Dimension*, gas quality monitoring would be characterized as centralized if a single (or handful of technologically comparable) entry point(s) monitor all gas for desired quality. It would be decentralized if the number and heterogeneity of the monitoring points increased. The *Institutional Dimension* can be interpreted in a similar way: it is centralized when all relevant decision rights are assigned to a single actor, and decentralized if the heterogeneity or the number of these actors increases.

In order to characterize the *Centrality of coordination*, we are interested in the number of gas system users, and the lines of communication between actors operating in different layers as specified by the Alignment Framework. In a Safety-I mode of management, we would expect a linear system with a limited number of nodes and connections where relevant decision rights are allocated to a small number of homogeneous actors. Conversely, in a Safety-II mode of management, we would expect a larger number of diverse nodes and connections with decision rights being allocated to a wider range of heterogeneous actors.

5.4.1.1. Adjustability of coordination. The adjustability of coordination refers to the degree in which devices for satisfying required infrastructure functioning are prescribed (Künneke et al., 2021). In the Technological Dimension, gas quality monitoring would be considered open if no specific instructions existed on *how* it was achieved. In other words, when the outcome (i.e., a certain bandwidth of gas quality) was prescribed but not the method (i.e., the type of monitoring device or location and operation thereof). Closed coordination describes a scenario with detailed instructions. In the Institutional Dimension, gas quality monitoring would be considered open if no specific instructions existed on *who* is responsible for monitoring, and via which operation procedures. Open coordination, for example, could be when decision rights are allocated to communities of users who re-allocate responsibilities among themselves. Closed coordination describes a scenario in which decision rights are ascribed to actors in detail.

A Safety-I mode of management is characterized by a high degree of standardization. The standardization of safety protocols, like task descriptions and compliance processes, might be required in a centralized system, if it is to monitor a growing number of system users and an associated higher frequency of communication (Provan et al., 2020). A safety-II mode of management would allow for more adaptability in task descriptions and compliance processes, for instance by allowing system actors to join up with the regulator to decide upon appropriate standards that are safe and effective for new technological or organizational developments (Wiig et al., 2020).

Table 3
Modalities of coordinating technology and institutions.

	Safety-I	Safety-II
Centrality of coordination (5.4.1.)	Centralized	Decentralized
Adjustability of coordination (5.4.2.)	Closed	Open
Scope of coordination (5.4.3.)	Monocentric	Polycentric

5.4.1.2. Scope of coordination. We introduce the scope of coordination to indicate the degree to which elements of a system are coordinated independently. In the technological dimension, a monocentric mode of coordination refers to the coordination of an autonomously functioning system element, such as a local gas grid which is not embedded in the larger gas infrastructure. Conversely, a polycentric mode of coordination refers a system where multiple systems, or system elements, interact in making the system function. An example of the latter includes complex systems, where effective coordination particularly includes a focus on the *interaction* among various system elements. In the institutional dimension, a monocentric mode of coordination is characterized by a single decision-making center, such as a utility organization involved in gas transport, distribution and retail. We refer to a polycentric mode of coordination when we can distinguish the existence of many or multiple decision making centers that are “formally independent of each other” (V. Ostrom et al., 1961, p. 831).

It is important to stress the difference between the centrality and the scope of coordination. Both are concerned with the number of users and technological artefacts that are to be coordinated, but they differ in their unit of analysis. The centrality of coordination is concerned with the *number of* units and how similar they are; the scope of coordination is concerned with the *relationship between* these units as they grow in number. A centralized and monocentric mode of coordination are generally alike. A decentralized mode of coordination, however, may be monocentric if it is characterized by the presence of many heterogeneous system components while having a single decision center.

A safety-I mode of management emphasizes the role of a central entity monitoring operations. This entity (i.e. a regulator) gathers information on system performance, and is concerned with attributing cause and responsibility for hazards and accidents, when the observed activities deviate from these requirements. A safety-II mode of management pursues an approach where multiple decision-making centers are involved with monitoring and enforcing safety management. The collaborative approach in which regulators and system actors cooperate provides an example. In the section below we apply these building blocks to study safety management in Netherlands gas provision.

6. Safety management in Netherlands gas Provision: The case of gas quality monitoring

6.1. *The Netherlands gas system*

Both the technological and the institutional arrangements that are relevant for safety management in the Netherlands’ gas industry are changing rapidly (Riemersma et al., 2020a). Within the wider context of the de-carbonization of the energy sector, the gradual phasing out of the supply of gas from the huge Groningen field in response to the earth tremors, a rapidly declining domestic natural gas production, and the threat of global natural gas supply disruptions in the wake of Russia’s invasion into Ukraine, new technological arrangements are required for renewable gas supply and distribution (Riemersma et al., 2020a).

Following the discovery of massive domestic gas resources in the province of Groningen in 1959, natural gas has become the main source of energy for the Netherlands. The country’s gas infrastructure is among the world’s most developed (Oxford Institute for Energy Studies, 2017), and provides gas to over 90 % of Dutch households, electricity generation, many industries and horticulture. It has also emerged as a prominent hub connecting the Northwestern European gas infrastructure (Riemersma et al., 2020a). Yet, gas from the Groningen field has a lower calorific value, compared to gas produced elsewhere in the Netherlands and abroad and traded internationally. As a path-dependent result, gas appliances in the Netherlands' households were attuned to Groningen-gas (G-gas) quality after the discovery of the field. In order to enable the use of its G-gas as well as the high-calorific gas (H-gas) deposits developed later, the Netherlands has built a gas infrastructure which involves dedicated pipelines for both types of gas (see Fig. 1). The G-gas transmission network is designed such that G-gas flows from the Groningen field to regional distribution grids, supplying smaller industry and households, and to export points at the borders. The H-gas network transports gas from domestic on– and off-shore fields and gas import points to large industries, power plants, export points, and G-gas conversion facilities. Gas quality is becoming an increasingly important topic, as gas supply becomes more diverse with the growth of imports and biogas production. This is reflected by the recently implemented requirement for grid operators to report deficiencies in gas quality or odorization since 2020 (Netbeheer Nederland, 2022b).

Declining domestic natural gas production increases the reliance on imports. Imported natural gas, typically by pipeline from Norway or Russia, but recently also more prominently as Liquefied Natural Gas (LNG by ship from the Middle East and The United States, must be modified by adding nitrogen. In order to reach the G-gas calorific value several plants have been created that modify imported gas, as is shown in Fig. 1. When blended with nitrogen, imported H-gas can be safely transported through existing G-gas infrastructure and combusted with existing appliances. Nevertheless, various quality regions exist. The growing heterogeneity of natural gas increases the possibility of gas quality deviations and thereby the need for gas quality monitoring (Riemersma et al., 2020b).

Biogas poses different challenges. Biogas production as a share of total gas consumption is still small (0.496 % in 2021), but it has seen a rapid increase from 0.06 % in 2012, and some estimate its overall share to reach 30 % by 2030 (CBS, 2018; Gasunie, 2018). This projected fast growth is a result of both the absolute growth of biogas production, but also of the decline in total gas consumption.

6.2. *Structure*

6.2.1. *Technological Architecture: A new system morphology*

The increasing decentralization of the Technological Architecture of Netherlands gas systems drastically increases the number of nodes that must be considered when managing safety. Fig. 2 shows how renewable gas can be injected at different points in the gas transmission system, and even at different points in the distribution system. As an example, three medium-scale and nine small-scale producers are depicted. All these producers require grid connections, and gas quality monitoring points. And, perhaps more importantly, also new grid connections (shown in red) are necessary to distribute excess production (Riemersma et al., 2020b). The monitoring points for biogas production increasingly are to be operated remotely. This adds an entirely new digital communication layer to the gas system's *Technological Architecture* that functioned primarily mechanically hitherto. Above developments make the operation of the gas system more complex, and prone to safety hazards that are emergent from unexpected, interacting, component interactions (ibid.).

6.2.2. *Macro-Institutions: A natural gas legacy*

The macro-institutional environment of gas quality monitoring in the Netherlands is heavily influenced by its natural gas legacy. Safety in gas provision had long been the competence of the integrated gas transmission and trading company Gasunie and a dozen of regionally operating gas distribution and sales organizations; the so-called gas companies. Under these institutional arrangements, which lasted through to 2004, the responsibility for the transmission of gas was exclusively assigned to Gasunie, which also coordinated gas purchases and wholesale in the Netherlands. Following the unbundling of gas transport from production and wholesale activities, the role of Gasunie changed. The Netherlands State became the sole owner of Gasunie, now named Gasunie Transport Services (GTS), and it's new role was restricted to operating the high-pressure gas transmission system, overseen by the Dutch regulatory authority.[4] GTS remains a central player in safety management. It is responsible, among other things, for maintaining and monitoring the quality of the gas before it is injected into medium-and low-pressure distribution systems (cf. Fig. 2). Regionally operating gas companies that operated these distribution grids and the retail sales were unbundled in a similar way. Rights for buying and selling gas, including retail sales, were assigned to gas traders. The task of distributing gas was assigned exclusively to regionally operating Distribution System Operators (DSOs). These operate as regulated regional monopolies, and are publicly owned by municipalities and provinces (Riemersma et al., 2020a). Small-scale and decentral biogas production is requiring DSOs, for the first time, to connect new producers directly to their grid.

6.2.3. *Changing modalities of Alignment*

Table 4 shows the difference between the degree of alignment in the Structure of natural gas and biogas provision. The table is elaborated on below.

The Structure of gas quality monitoring in the natural gas system is characterized by a centralized mode of coordination. A list of standardized gas quality parameters exists, and the Gas Act stipulates how, when and where this quality must be achieved.[5] Producers and importers of natural gas are responsible for delivering gas with certain quality requirements to the grid. Subsequently, GTS is responsible for delivering the gas of a particular quality to large customers and the regional grid operators, as well at the export connections. These clear technological and institutional responsibilities point to a closed mode of coordination. This scope of coordination suggests instances of misalignment due to the increasing system complexity. Macro-Institutions that remain mono-centric are increasingly at odds with a Technological Architecture that features more instances of non-linearity and digitization, both of which independently influence system behavior and render the system more polycentric.

The Structure of gas quality monitoring for biogas is significantly different. In an increasingly decentral mode of coordination, biogas monitoring occurs at a growing number of heterogeneous biogas production locations. It takes place for different types of biogas production facilities, at different spatial locations and nodes in the gas system. The institutional arrangements suggests a similar decentral mode of coordination, as the responsibility for gas quality is allocated to individual producers of biogas.[6] These producers are growing in number, and range from dairy and pig farmers to operators of waste treatment facilities. The technological coordination of biogas quality monitoring is characterized by a closed mode of coordination. Clear quality parameters for biogas exist, and monitoring equipment is subject to regular inspection and certification. The same is not true for institutional coordination, however. The responsibility for maintaining a certain gas quality (allocated to DSOs) is no longer bundled with that for gas quality monitoring (allocated to producers). Therefore, a need arises for bilateral or multilateral arrangements between DSOs and the biogas producers that now should guarantee their adherence to a specified gas quality

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[4] For further information on functioning of the newly created system, the roles of the transmission and distribution system operators, and the firms carrying out the commercial tasks of production and trade see (Correlje, 2016; Correljé, 2005; Riemersma et al., 2020a).

[5] MR Gaskwaliteit, with respect to Article 11.1 of the Gas Act.

[6] Meetcode gas RNB, Article 5a.1.1.

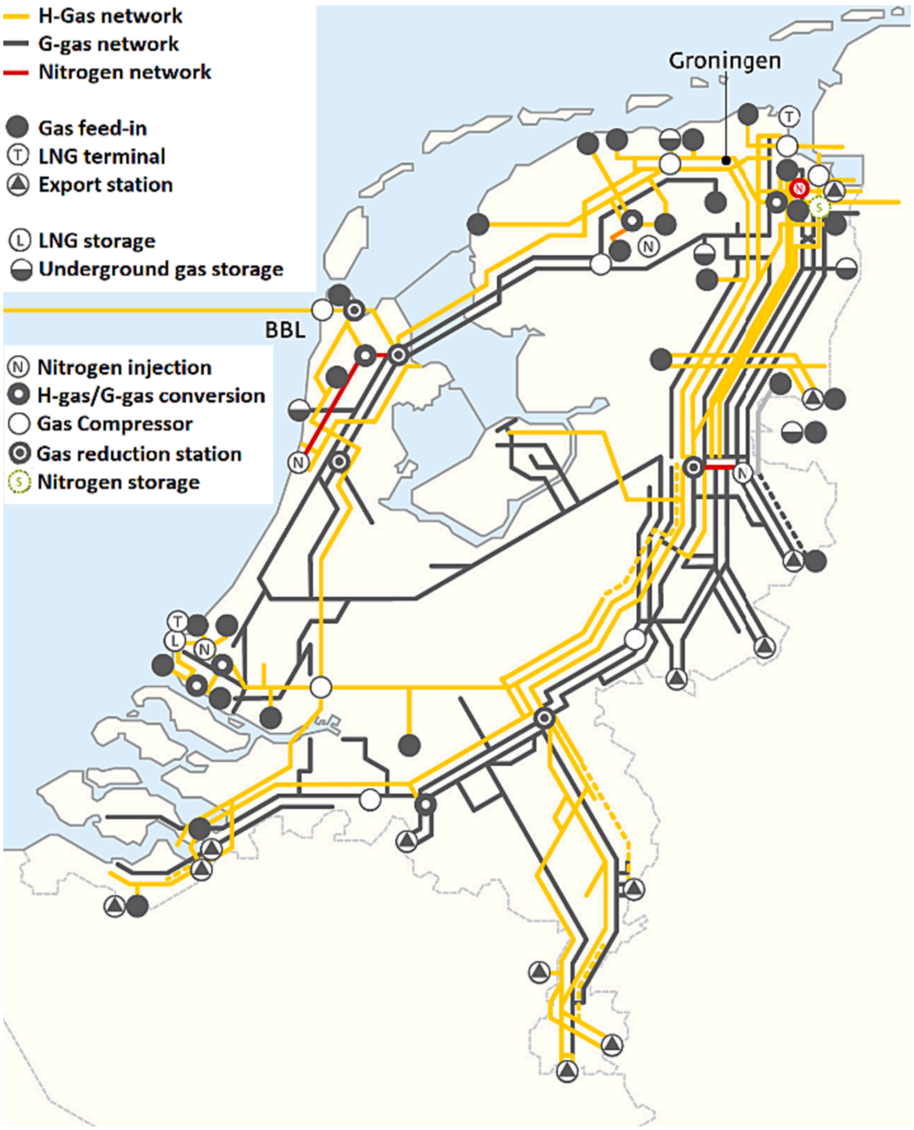

Fig. 1. The Netherlands Gas Transmission Network, translated and updated from gasunietransportservices.com by the authors.

(personal communications, cf. footnote 2). This instance of misalignment influences various decisions along different layers of our framework, as will become clear below. The scope of coordination for biogas quality monitoring is equally non-aligned. The technological coordination is polycentric, as the system is growing more heterogeneous and the associated system behavior becomes increasingly unpredictable (Riemersma et al., 2020b). The institutional dimension, however, is monocentric. The regulator plays an important role in interpreting, allocating, monitoring and enforcing decision rights. The next section explores this further.

6.3. Governance

6.3.1. Technological Design: Increasing diversity of gases

The decreasing domestic production of G-gas increases the reliance on other types of natural gas and renewable gasses. The most prominent natural gas alternatives are indigenous or imported H-gas and LNG. H-gasses are blended with varying volumes of nitrogen to adapt the calorific value before they can be injected into the dedicated G-gas system, including all medium and low pressure grids. As a result, a growing reliance on H-gas imports creates a higher reliance on nitrogen mixing facilities. The growing heterogeneity of natural gas sources increases the importance of quality monitoring. Renewable gasses pose new challenges altogether. Biogas must be monitored for all kinds of different hazardous components, and thus requires different monitoring equipment. Moreover, it is important to shut down gas supply *immediately* once off-specs gas is detected, because of the close proximity of small-scale biogas producers to the location of consumption. Therefore, monitoring arrangements generally involve information technology to enable real-time enforcement.

The new gas connections illustrated in Fig. 2 indicate possible gas monitoring locations. The need to install actual monitoring devices will depend on how much gas must be transported *upwards* in the gas grid and how much must be transported to adjacent grids, possibly operated by different DSOs. This, obviously, will depend on the methods of dealing with supply surpluses. Local storage capacity, for example, might reduce the need for inter-connection of the grids altogether. Similarly, financial incentives might remedy such surpluses by curtailing supply or stimulating demand at critical moments. Nevertheless, as biogas will be produced mainly in remote agricultural areas, while being consumed in industrial areas and nearby urban centers (Riemersma et al., 2020b), interconnection will become a crucial element of the technological design.

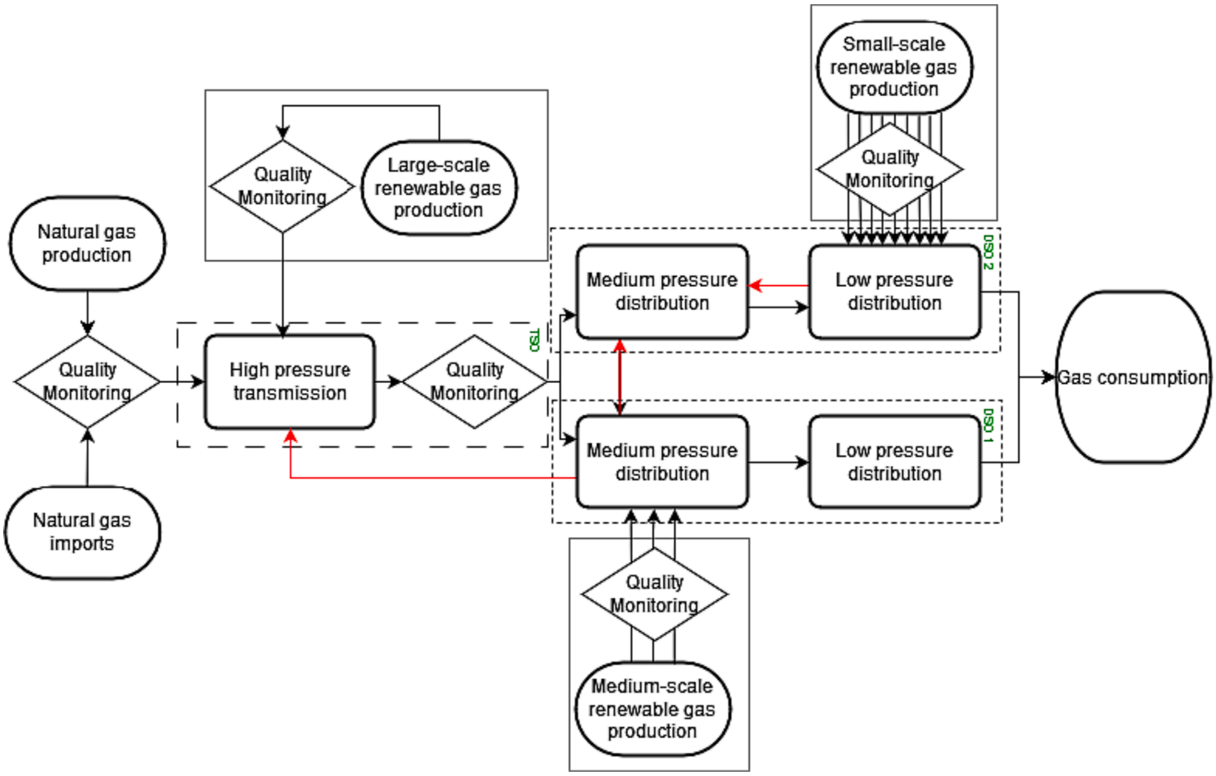

Fig. 2. Future gas grid with multiple types of gas producers (Figure by authors).

Table 4
Degree of Alignment in the Structure of Gas Quality Monitoring.

	Natural Gas		Biogas	
	Tech. Architecture	*Macro-Institutions*	*Tech. Architecture*	*Macro-Institutions*
Centrality	Centralized	Centralized	Decentralized	Decentralized
Adjustability	Closed	Closed	Closed	Open
Scope	Polycentric	Monocentric	Polycentric	Monocentric

6.3.2. Meso-institutions: Need for monitoring gas quality

The most important actors operating in the Meso-Institutional layer are regulators and grid operators (Künneke et al., 2021, pp. 100–102). Albeit in different degrees and capacities, both interpret and implement rights and rules. We distinguish among two important regulators. The Authority for Consumers and Markets (ACM) and State Mining Supervision (SodM) operate respectively as economic and safety regulators. The ACM interprets and specifies the implementation of the Gas Act through a set of codes that regulate particular technological or institutional developments. Tariff codes specify the rates that grid operators may charge shippers for using the grid. Information codes specify the conditions under which information is exchanged by various users of the grid (and whether this is required or prohibited). Technical codes specify responsibilities and rights of grid operators, gas producers, shippers and gas users. Grid operators, jointly represented in Netbeheer Nederland, influence this process as well. They are authorized to propose and comment on changes in tariff and technical codes. These three actors are informed and advised by a wider group of 'grid-users', including traders, large users, providers for energy technology and retail companies, that can comment and suggest changes in the information code.[7]

Technical codes show significant differences in decision rights that are allocated to both types of grid operators to execute their responsibilities. The TSOs can modify gas quality in case of non-compliance.[8] The operation of nitrogen facilities to modify gas exports is instrumental in this respect, as well as their ability to blend incoming flows of gas from different fields. DSOs, in contrast, do not have a comparable mandate or obligation to modify the gas quality. With respect to the interconnection of the transmission and distribution grid, technical codes specify how the TSO must monitor gas quality before transferring the gas into the distribution grid and how it should communicate gas quality parameters to DSOs. The TSO is also required to remedy any causes for non-compliant gas inflows when that is observed in their own operations, or when this is notified by the DSOs.[9] Biogas monitoring works differently. A special provision for biogas connections allocates the responsibility for monitoring biogas quality to the producers, and requires them to install monitoring equipment that meets specified requirements.[10] This equipment must be regularly checked and certified, while specified information must be documented and relayed to the DSO on a regular basis.[11] The technical codes specify that the DSO may refuse biogas producers' access to the grid when off-specs gas is identified.

The SodM carries out investigations, monitors accident data and establishes directions for safety management accordingly. It requires grid operators to register and communicate multiple types of gas-related incidents. Category 1 incidents are those where no people have gotten injured or deceased, and fewer than 250 people had to be evacuated;

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[7] https://www.acm.nl/nl/onderwerpen/energie/de-energiemarkt/codes-energie/wijziging-van-codes-energie.

[8] Aansluitcode gas LNB, Article 5.

[9] https://wetten.overheid.nl/BWBR0037919/.

[10] Aansluit- en transportcode gas RNB (English: Connection and transport codes Distribution System), derived from https://wetten.overheid.nl/BWBR0037926/2020–04-04.

[11] Meetcode Gas RNB (English: Measuring Code Gas Distribution System), derived from https://wetten.overheid.nl/BWBR0037925/2021–07-03/#Hoofdstuk2, last accessed September 13th 2021.

category 2 incidents are those with injury or death, or where more than 250 people needed to be evacuated (SodM, 2020). This data is used by grid operators to analyze trends (Netbeheer Nederland, 2022a), and by regulators to guide monitoring and enforcement (SodM, 2022). To illustrate, a 2019 high profile gas explosion in The Hague that injured 10 people was attributed to decaying cast-iron mains, and resulted in the SodM mandating a faster phase-out of their usage (SodM, 2022).

6.3.3. *Changing modalities of Alignment*

Table 5 illustrates the degree of alignment in the Governance of natural gas and biogas provision. The table is elaborated below.

The technical Governance of natural gas quality monitoring is increasingly more decentral. While the natural gas architecture still supports a top-down gas flow, its design must account for a larger role for nitrogen facilities and LNG regasification plants. Even so, relevant decision rights remain centrally allocated. GTS is responsible for monitoring and enforcing gas quality, under regulatory supervision of the ACM and SodM. As a result, technological and institutional devices that characterize the centrality of coordination are not fully aligned. The adjustability of coordination is closed for both dimensions, as the TSO ensures a stable gas quality that is tightly specified by relevant codes. The plurality and diversity of instances where and how natural gas enter the system renders the design less monocentric, but the continued top-down gas flow and stable gas quality keep system behavior fairly predictable. The institutional scope of coordination, likewise, remains monocentric as GTS continues to be the single prominent actor involved with securing natural gas quality.

The Governance of biogas quality monitoring shows a significant discrepancy. The technological centrality of coordination will decentralize to a much wider extent than that for natural gas. This is illustrated by the increase in the *number* of production locations that are all injecting biogas into the distribution grid, from 36 in 2017 to 65 in 2022.[12] Institutional centrality of coordination remains in place. Even if obligations for monitoring have been decentralized to biogas producers, relevant decision rights such as those regarding enforcement remain tightly coordinated with the regulator and, to a lesser extent, the DSOs. Interviews with grid operators suggest instances of misalignment in the adjustability of coordination, where clearly prescribed technological methods to modify or enforce gas quality exist, while institutional arrangements remain underspecified. Therefore grid operators are pursuing different monitoring and enforcement approaches, as will be shown in Section 6.4 below. The scope of coordination, finally, is certainly more polycentric in comparison to its natural gas counterpart, in both the technological and institutional dimension. Real-time gas quality monitoring adds a digital component to the system for gas quality control. The control over new infrastructure connections such as shown in Fig. 2, will rely on digital devices to enable real-time enforcement. These devices are crucial for coordinating the more bi-directional mode of transport and localized gas production. Moreover, they depend on different infrastructures, like internet and electricity, therewith embedding gas systems in other socio-technical systems. The institutional dimension also exhibits polycentricity, involving various DSOs and heterogeneous groups of biogas producers independently assuming responsibility for managing safety in various segments of the grid. Moreover, as biogas production often takes place in the rural parts of the country, variation arise in the degree to which different regional DSOs are affected by these developments.

Table 5
Degree of Alignment in the Governance of Gas Quality Monitoring.

	Natural Gas		Biogas	
	Tech. Design	*Meso-Institutions*	*Tech. Design*	*Meso-Institutions*
Centrality	Decentral	Central	Decentral	Central
Adjustability	Closed	Closed	Closed	Open
Scope	Monocentric	Monocentric	Polycentric	Polycentric

6.4. *Transactions*

6.4.1. *Technical Operation: New operational choices*

The growing embeddedness of gas systems in the wider system of infrastructures, as well as the increasing complexity of their Architecture and Design, introduces a range of operational choices for both natural gas and biogas distribution. To understand the impact of this scenario, we focus on a very straightforward gas system component: the shut-off valve. This mechanism works to facilitate or stop the transfer of gas from two connected gas grids with a different pressure. An open valve will allow gas to flow from a high to a low pressure pipeline. In a traditional top-down *Architecture*, this component generally functions purely mechanically. It is designed so that the valve opens when the pressure in the receiving grid drops below a certain point, and that it closes when the receiving grid has reached the preferred pressure level. In the traditional technological design, no other variables than *pressure* influence the simple decision of 'valve open' or 'valve closed' in the whole of the system. We have shown above that in the new design, this decision involves more requirements, such as *gas quality* specs, a functioning *IT* system, and the presence of electric power.

Remotely operated shut-off valves function electronically. A control room gathers relevant information on the preferred status of the valve, and operates the valve accordingly. In addition to the receiving grid pressure being lower, the valve status must now also consider gas quality. This immediately poses the question what to do in the case of a lack of data, for example when a power outage disrupts the information flow. Indeed, power outages caused twenty-one disruptions in odorization equipment in 2021, making up a significant amount of the total of twenty-nine total odorization errors reported (Netbeheer Nederland, 2022b). Grid operators might install their control valves in such a manner that they automatically close in the case of a power outage, so that no off-spec gas is let through. The way in which these valves are installed, and the parameters chosen, depend on how grid operators act in the prevailing institutional environment.

6.4.2. *Micro-institutions: Between formal and informal Institutions*

The transfer of gas, considering the responsibility for its quality, from the transmission to the distribution grid is governed under the conditions set forth in Section 6.3. Even if procedures for dealing with off-specs gas, and repercussions for those responsible, are laid out in codes, this particular transaction is partially governed by informal institutions as grid operators interpret and act upon these codes in their own way. In addition to the specified decision rights above, our interviews with grid operators (see footnote 2) suggest that DSOs by and large trust natural gas to meet specifications by the time it enters the grid, following decades-long of successful cooperation. However, with the share of biogas and different sources of natural gas in the transmission segment growing, concerns are starting to emerge concerning the lack of formal enforcement mechanisms in case of off-spec gas delivery. These concerns are rooted in a belief that the likelihood of off-spec gas entering the grid will increase with a growing heterogeneity of natural gas. The well-known natural gas based system, and the associated gas quality monitoring governance that was tried and tested, has to make way for a variety of different gasses and evolving quality monitoring governance.

Under the current governance, interviewees of two grid operators observe two distinct modes of coordinating biogas quality monitoring. In the first mode, grid operators install separate monitoring facilities at biogas production plants. This enables them to independently verify gas quality and, if necessary, to remotely disconnect the producer from the

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[12] https://www.netbeheernederland.nl/dossiers/groen-gas-18.

grid. Yet, for the DSO to install monitoring equipment is not part of their responsibilities as formulated in the Gas Act. In the second mode, grid operators follow prevailing institutional arrangements and do not install monitoring equipment, which becomes the responsibility of the producers. Grid operators then rely on the accuracy of data they receive from the biogas production plant. Uncertainty about the accuracy of the monitoring process, or the condition of the materials and devices used, is partially remedied by technical codes requiring the biogas producer to certify its equipment periodically through licensed parties. The decision for additional monitoring, then, is influenced by the trust of grid operators in the accuracy of the gas quality control and monitoring at biogas production facilities.

6.4.3. Changing modalities of Alignment

Table 6 shows the degree of alignment in the Transaction layer of natural gas and biogas provision. The table is elaborated below.

In natural gas systems, the technical coordination of gas quality monitoring is centralized. Gas is monitored at selected points in the transmission system. The institutional coordination, likewise, is centralized and tightly controlled by GTS. Looking at the adjustability of coordination, the technical coordination is closed as gas quality parameters are strict, while the institutional coordination is relatively open. We explained how transferring gas from the TSO to DSO grids is formalized, but remains partially trust-based. In other words, differences may exist (or emerge) with respect to how the TSO interacts with various DSOs. Additionally, a variety of technological developments, like the inflow of gasses prone to quality problems, might influence and shape these existing relationships, as certain decision rights remain ungoverned by network codes and entry and exit contracts. The scope of coordination is aligned and monocentric in both technological and institutional dimensions. The technologies used to monitor natural gas quality operate mostly without affecting other system components, and relevant decision rights are allocated to only grid operators.

Biogas quality monitoring takes place at a growing number of production sites by a heterogeneous group of biogas producers, and thus shows a highly decentralized mode of coordination. The technical coordination of quality monitoring is closed as clear parameters exist. In contrast, the institutional coordination is open, to a much larger extent than with natural gas. While responsibilities with respect to gas transport are allocated by regulators, a variety of micro-institutional arrangements already exist to meet them. Some grid operators adhere strictly to the prevailing rules and keep gas quality monitoring at arm's length, while others have chosen to internalize gas quality monitoring in such a way that they can oversee the process themselves. Our interviews with grid operators show that there are several arguments that determine whether a DSO prefers one arrangement over the other. These includes their risk assessment, relationship with the gas producers, and trust in the regulatory process and the mandatory certification of monitoring equipment. Finally, the scope of coordination is decidedly polycentric in both dimensions. On the one hand, technical coordination is increasingly digitized, resulting in embedded systems that influence—and depend on—each other. On the other hand, institutional coordination increasingly involves multiple decision making centers. This is already true in distribution grids, with both biogas producers and DSOs involved in gas quality monitoring, and will become more pronounced as distribution grids are interconnected and when they will be injecting gas into higher pressure grids.

Table 6
Degree of Alignment in the Transactions Layer of Gas Quality Monitoring.

	Natural Gas		Biogas	
	Tech. Operation	*Micro-Institutions*	*Tech. Design*	*Micro-Institutions*
Centrality	Centralized	Centralized	Decentralized	Decentralized
Adjustability	Closed	Open	Closed	Open
Scope	Monocentric	Monocentric	Polycentric	Polycentric

7. Discussion: Safety management in gas quality monitoring

Gas quality monitoring and enforcement for both natural gas and biogas is currently characterized by a mode of safety management resembling Safety-I. It is reliant on compliance, as regulators primarily define safety priorities based on past performance indicators such as supply disturbances and incident-reporting. This mode of safety management, centralized, closed, and monocentric, was well attuned to technological features of the conventional natural gas infrastructure that is equally centralized, closed and monocentric. It may not, however, sufficiently incorporate new technological and spatial features in both natural gas and especially biogas provision. We identify instances where elements of Safety-II would more closely bring safety management into line with evolving gas systems.

An increasingly polycentric *Technological Architecture* requires a more polycentric *Macro-Institutional* environment. Technological polycentricity in conventional natural gas systems is growing, and already high in new biogas systems. Currently, a limited number of authorities yield sufficient rule-setting capacity to change or modify relevant decision rights, so that new (types of) safety hazards are no longer appropriately identified, prevented or mitigated. In contrast, a more polycentric Macro-Institutional environment would include authorities of varying levels, types and sectors but also facilitate *overlapping jurisdictions* (Baldwin et al., 2018; McGinnis, 2011; E. Ostrom, 2005). In practice, this would entail more frequent communication but also collaboration by European, National and local authorities as well as grid operators and suppliers of essential technologies (Goldthau, 2014). In line with the Meso-Institutions that already exist for determining the various gas codes, collaborative platforms, applying hands-on information, could become engaged in setting safety guidelines for emergent technologies.

A further decentralization of *Meso-Institutions* may restore alignment in safety *Governance*. The increasingly decentral nature of gas provision adds a variety of new technological artefacts and system users. In the current Safety-I mode, this growing number of system elements and their interaction is creating a significant increase in pressure on the two regulators, as they have to interpret the monitoring information produced by mandatory reporting of grid operators in the light of relevant Macro-Institutions. Incorporating elements of Safety-II would allow for a wider range of actors to be involved in defining, monitoring and enforcing decision rights (Hallack & Vazquez, 2014; Leistikow & Bal, 2020; Menard et al., 2021; Salter & Tarko, 2018). DSOs, for example, could be allocated more responsibilities in monitoring the quality of gas before it enters the grid, in combination with a wider mandate for selecting appropriate practices for gas quality modification.

Our analysis identifies misalignment in the *Transaction* layer for both natural gas and biogas. We identified how prevailing micro-institutional arrangements, embedded in contracts, guidelines and trust-based relationships, are not fully capable of mitigating the increased uncertainty emerging from the growing heterogeneity in gas quality and the larger number of producers. Alignment can be restored by allowing either a more *open* technical operation, or more *closed* micro-institutional arrangements. A Safety-II approach would call for the former, and create more flexibility in gas quality parameters and the choice of technological devices chosen for gas quality monitoring. More flexibility in gas quality parameters could, for example, allow for a wider gas quality bandwidth, if joined with credible enforcement mechanisms. More flexibility in technological devices could result in grid operators and gas producers to jointly decide on the preferred, locally adequate, technological solutions for gas quality monitoring.

8. Conclusion

This analysis of future gas transport systems guides the implementation of a Safety-II style of management. It is structured around the compatibility of its technological and institutional coordination. Our novel application of the Alignment Framework provides researchers and practitioners of safety management, specifically in the nascent field of Safety-II and systemic approaches to safety management, with additional tools for analyzing rules, their relationship to technology and the different ways in which they can be interpreted, translated, monitored and enforced.

Our analysis demonstrates that the prevailing mode of Safety-I management is not in harmony with the increasingly complex technological and transactional arrangements in gas systems. We show how a rapidly changing technological architecture requires more polycentric institutional arrangements, and argue for a wider range of system users to be involved in defining and allocating relevant decision rights for safety management. The rapid and ongoing technological decentralization of both natural gas and biogas provision puts pressure on the current regulatory approach, which is based on centralized enforcement and monitoring responsibilities. We suggest that the decentralization of enforcement mechanisms, for example by allowing DSOs to modify gas quality, restores alignment in the governance of gas quality monitoring. Finally, we highlight the increasing importance of bilateral relationships among grid operators, or between grid operators and gas producers. We suggest that an increasingly heterogeneous gas supply and the associated dispersion of information calls for different monitoring and enforcement mechanisms. This could involve either the further formalization of trust-based relationships between DSOs and producers, or more flexibility in choosing preferred technical solutions for monitoring new gasses.

Our method of integrating Institutional Economics and Safety Science provides valuable lessons for the study of safety in many systems. The layered approach of the Alignment Framework, in combination with insights from the Safety-II literature, enables not only the analysis of safety management in gas systems, but other complex infrastructure systems more generally. As a general tendency in infrastructure provision, we observe that there is a development towards a greater technological variety and decentralization, while a much wider group of actors is involved with often different abilities and preferences. It is in this context that the notion of polycentricity is becoming relevant, in association with the study of Institutional Economics as well as the Safety-II approach. This study provided the first steps in doing by introducing a taxonomy for assessing safety in complex socio-technical systems. Even so, more empirical validation is required to assess our conceptual contributions. Our data covers a limited segment of a single country's gas system, and this paper provides high-level directions. The next step in the current research will zoom in on the Governance layer, and provide detailed recommendations for allocating translating, monitoring and enforcement responsibilities based on prevailing technological arrangements. We invite other researchers to further exploring and developing this approach, and believe it could provide valuable insights other complex technological systems. This holds true for energy systems, but also in fields as diverse as the banking industry or water management that witness the decentralization and localization of infrastructure resource provision.

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CRediT authorship contribution statement

Ben Riemersma: Writing – original draft, Methodology, Investigation, Conceptualization. **Aad F. Correljé:** Writing – review & editing, Supervision. **Rolf W. Künneke:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Ben Riemersma reports financial support was provided by Netbeheer Nederland].

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