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Historical developments in Dutch gas systems: Unravelling safety concerns in gas provision

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ABSTRACT

This paper identifies safety concerns that arise from ongoing technical and institutional changes in the Dutch gas sector. The Netherlands has a well-developed gas infrastructure that primarily transports natural gas, although its constituting features are undergoing major changes. We identify three historical developments, and show how (1) ongoing effects of liberalization; (2) earthquakes in the Groningen-area; and (3) commitment to climate goals affect safety. Between trends of ongoing decentralization and a growing variety of gas producers, the most urgent concerns relate to the operation of low- and medium pressure distribution grids. Natural gas is losing its prominent role, leaving system operators faced with trade-offs induced by a declining share of customers. At the same time, responsibilities for new gas technologies are allocated over a growing number of actors. In illustrating how safety practices have evolved in line with incremental technological and institutional developments over the last half century, this article elaborates how sudden changes in constitutional features of infrastructural systems might jeopardize system safety.

1. Introduction

The gas sector in the Netherlands is facing fundamental challenges. Incremental and sudden changes render outdated existing safety practices that were developed over the past century. The imminent termination of production from the natural gas field in the province of Groningen, for example, is set to radically change the country's energy provision. Currently, this field is vital to the Dutch energy supply and is a key source of energy for neighboring countries. Yet since the mid-1980s, gas production has been causing a series of increasingly forceful earthquakes in the Groningen area that damaged houses, business properties, public buildings and monuments. Civil unrest and massive protests resulted in mitigation measures: in March 2018 the Dutch government announced its objective to fully terminate the production of the field by 2030. The phasing out of Groningen gas (G-gas) severely limits domestic natural gas supply, leaving the Netherlands largely dependent on imports of natural gas or, increasingly, renewable gasses.

Indeed, earthquakes in the Groningen area are not the only development shaking the Dutch gas landscape. We identify two other historical developments: the ongoing effects of gas sector liberalization as well as the commitment to climate goals. Liberalization has added competition in gas supply and made it easier for new gas producers to enter the market. Additionally, commitments to reduce CO_2 emissions are leading to increased production of green gas and, potentially, hydrogen gas (both will be introduced in Section 3.3). These *renewable gasses* hold a significant role in future energy scenarios in the Netherlands (Eker and Van Daalen, 2015; Netbeheer Nederland, 2018a) and neighboring countries (Dodds and Mcdowall, 2013; Poeschl et al., 2010; Speirs et al., 2018). Despite the abundance of literature on renewable gasses, or alternatives to natural gas more generally, no studies provide a comprehensive overview of the way ongoing transitions affect safety.

Studies that focus on safety in gas provision tend to be limited in scope, whereas articles that study ongoing transitions in the gas sector largely neglect safety. To illustrate, safety has been investigated with respect to gas quality standardization (Schweitzer and Cagnon, 2011; Zachariah-Wolff et al., 2007), carbon monoxide poisoning (Brunekreef et al., 1982; Onderzoeksraad voor Veiligheid, 2015; Simpson and Calnan, 1973); odorization (Amirbekyan and Stylianos, 2013; Butenko, 2014; Kilgallon et al., 2015; Tempelman and Butenko, 2013); and renewable gasses (De Santoli et al., 2017; KIWA, 2018a; Labidine Messaoudani et al., 2016), but these studies do not take into account ongoing changes in their respective fields. This is also true for studies that apply a wider scope to safety (Boccard, 2018; Maslen, 2015; Wijnia and Hermkens, 2006). Analyses of transitions within the gas sector, then, barely address safety issues or not at all (Correljé, 2005; Dodds and Mcdowall, 2013; McGlade et al., 2018; Poeschl et al., 2010; Weidenaar et al., 2012). Two recent studies of gas networks in the United Kingdom (UK) are exceptions to this (Arapostathis et al., 2019a; Hanmer and Abram, 2017). This research gap is worrisome because the conditions around which current safety practices have evolved change rapidly. For example, existing appliances may not safely combust

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renewable gasses and new actors emerge that do not readily fit in governance structures that were developed for a monopolistic gas enterprise with heavy state involvement. Safety issues surrounding renewable gasses and liberalization are present in many countries, but—as shall be further explored below—are particularly pressing in the unique case of the Netherlands. Hence, this article addresses the following question: *how do recent historical developments in the Dutch gas sector jeopardize system safety?*

We relate the identified historical developments to four safety concerns: non-standardized gas quality, inadequate appliances, loss of system control and underutilization. Driven by institutional *and* technical decentralization, as well as a growing number of actors associated with gas provision, the distribution segment of the gas grid becomes increasingly important. These findings warrant a reevaluation of the governance of safety that was traditionally associated with the centrally organized transmission segment. This article is structured as follows. First, the methodology is shortly outlined in Section 2. Section 3 identifies three historical developments in the Dutch gas sector, and describes their impact for gas transmission and distribution. Section 4 identifies safety concerns associated with the ongoing changes in the Dutch gas sector and analyzes the hazard profile. Section 5 discusses the implications of the findings and suggests paths for further research.

2. Methods

Historical developments and safety concerns were identified through semi-structured expert interviews as well as from a literature review. This resembles recent studies address safety in UK gas networks (Arapostathis et al., 2019a; Hanmer and Abram, 2017). The interviews were typically held face-to-face and averaged approximately 45 min in length. An overview is provided in the Appendix A. The style of interviewing corresponds with what Rubin and Rubin (2005) refer to as the “open the locks” and “tree and branch” styles, i.e. characterized by an exploratory nature of the questions, and allowing for the identification of specific issues that merit further attention. Interviewees were asked about developments in the Dutch gas sector; their vision for gas networks in the Netherlands; organizational or technical challenges they faced; what they considered urgent or imminent safety concerns, and were encouraged to share specific examples.

The historical developments and safety concerns identified in the interviews were substantiated by a comprehensive literature review. The review was conducted on ScienceDirect and Scopus, two major databases that accumulate a wide range of academic and technical literature, as well as reports issued by a variety of institutes. In order to identify changes in the Dutch gas sector, we searched for “Gas AND Netherlands”, in combination with for example “Network OR Infrastructure OR System”, “Future”, “Groningen OR Depletion”, “Liberalization OR Liberalisation”, “Trade OR TTF OR Gas Hub” or “Hydrogen OR Biomethane OR Biogas OR Green Gas”. The articles were scanned for their relevance, which resulted in 101 unique articles. This literature review provides the backdrop for the three historical developments that shape Section 3. All articles were scanned for relevant information regarding threats to safety, after which identified concerns were clustered to structure Section 4. Both sections rely on input from expert interviews, as well as on literature sourced from a variety of institutes and system operators.

3. Historical developments in the Dutch gas sector

3.1. Liberalization

3.1.1. Historical developments

Gas exploration, production and provision have historically involved both private and public parties. Significant gas networks already existed before the 1959 discovery of the Groningen field induced the development of a national gas infrastructure. The first gas companies were established in the early 19th century, with the gas primarily used for street and domestic lighting. From the mid-19th century municipalities assumed a prominent role in the production and distribution of gas. The discovery of large coal resources in the southern province of Limburg resulted in the establishment of a state-owned mining company *Staatsmijnen* (later named Dutch State Mines, or DSM), responsible for the production of coal, as well as for the manufacturing of coke and city gas and coal-based chemicals. Together with the province of Limburg and several municipalities, DSM became responsible for the first regional gas distribution networks in 1934. Apart from a small amount of larger distribution grids in the southern part of the Netherlands and in the province of North-Holland, the majority of gas companies was limited in scale and operated by municipalities (Waszink, 1996). Small-scale exploration of natural gas started in 1947 with the establishment of the Dutch oil and gas exploration company NAM – a 50/50 joint venture between the Dutch Government and two oil companies Shell and Exxon/Mobil (then called Esso). Arrangements for the division of revenues from the large Groningen field were made in 1962, resulting in the so-called *Dutch gas building*. NAM was responsible for producing gas from the Groningen field and other on- and off-shore concessions. A newly established founded venture, Gasunie, coordinated gas purchases and sales, and was responsible for building and operating a national high-pressure (67–80 bar) transmission system to transport gas across the country. Gasunie was owned by the Dutch State Mines (DSM, later EBN)[1] (40%), the Dutch government (10%), and Shell and Exxon/Mobil (25% each). Gas for domestic consumption, as well as for small- and medium-sized industrial plants and businesses, was distributed through to medium- (4–8 bar) and low-pressure (300–100 mbar) distribution grids that were operated by public municipal or regional gas utilities. These companies bought their gas requirements from Gasunie. Particularly over the 1980s and 1990s, gas utilities increasingly merged into larger, regionally operating, companies supplying both gas and power. This governance of the Dutch gas sector remained in place until 2004 (Correljé, 2011; Correljé et al., 2003). Fig. 1 provides an overview, and also shows how liberalization changed this structure after 2004, as further explained below.

At the turn of the century, the Dutch gas sector was reorganized along the lines of European Union directives to restructure and liberalize energy markets (Correljé, 2005). Sector governance had thus far been based on private contracts, negotiation and deliberation between few public and private actors (i.e. the state, Shell, Exxon and the municipalities and their distribution companies) (Gastec, 2003). Introducing competition and more private sector initiative in the gas market was to stimulate economic efficiency to achieve a lower cost energy supply. The provision of natural gas as a commodity was unbundled from the ownership and operation of networks. In other words, the provision of gas is organized as a commercial activity between competing private firms, whereas gas networks are public utilities owned by municipalities, provinces, or the Dutch state. Hence, the transmission- and distribution system operators (TSO and DSO) are no longer engaged in commercial activities. Accordingly, technical and economic rights and responsibilities were redistributed among incumbents and new actors in the gas sector. The now fully state-owned Gasunie retains its responsibility as TSO delegated to its regulated subsidiary Gasunie Transport Services (GTS). The commercial activities related to almost all indigenously produced gas have been transferred to Gasterra—a newly established company with an ownership structure similar to the formerly monopolistic Gasunie. Gasterra sells gas to national and international retail companies, traders, and large industrial customers.

[1] EBN is currently a limited liability company the shares of which are fully owned by the Dutch government. On behalf of the Dutch State it participates in the exploration and exploitation of Dutch oil and natural gas resources. Source: https://www.ebn.nl/en/about-ebn/history/ (accessed last January 30th, 2019).

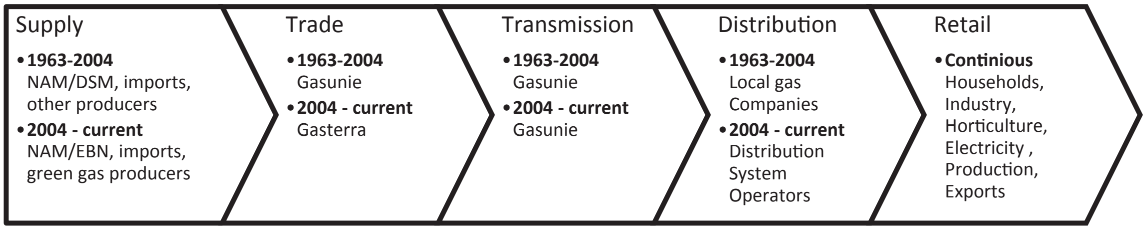

Fig. 1. Market and ownership structure of the Dutch gas industry.

The position of the NAM and the production concessions for domestic gas field remain unchanged. An energy regulator (DTe, now ACM) was established to implement the new Gas Act, including the economic regulation of the networks and the creation of a competitive gas market (Correljé, 2005). In this new governance structure, gas is traded both under bilateral contracts and, increasingly, via the Title Transfer Facility (TTF)—a marketplace that enables all parties (shippers) to sell and buy volumes of gas that have been injected into the Dutch transmission grid, at the prices established at the Dutch gas exchange (Schipperus and Mulder, 2015).

3.1.2. Implications for gas provision

The liberalization of the Dutch gas sector had significant implications for the governance of both the transmission and distribution segments of the grid. An illustrative example is the balancing of the transmission network. Prior to liberalization, Gasunie coordinated both trade and transmission. By combining oversight on and control over gas supply and demand patterns and storage capacity, it was able to maintain a secure supply and keep the transmission grid within the required pressure levels for safe transport. While Gasunie is still responsible for grid maintenance and transmission through its subsidiary GTS, other functions—such as short-term balancing of demand and supply—are increasingly left to other actors under an incentive structure only coordinated by GTS (Van Dinther and Mulder, 2013). These functions have especially changed for renewable gas provision, as will be discussed below (Section 3.3).

The main roles and responsibilities in the distribution part of the grid have traditionally been assumed by the municipal-owned gas utilities who, in their current role of DSO, remain key actors in the safe delivery of gas. Still owned by municipalities and provinces, a total of seven DSOs are assigned to dedicated areas and are regulated as a natural monopoly. Their tasks entail maintaining the existing distribution grid, (dis-)connecting customers to or from the network and modernizing the network to make it suitable for future developments. Like the TSO, DSOs cannot engage in any commercial tasks and are dedicated to the efficient and effective distribution of gas.[2] This has shifted certain responsibilities for safety towards the private sector (Section 4.2), and also bears implications for the safe production of decentral produced renewable gas (Section 4.3).

3.2. Earthquakes in the Groningen area

3.2.1. Historical developments

From the mid-1980s, increasingly forceful earthquakes took place in Groningen, caused by the gradual reduction of the pressure in the field. In 2012, a strong earthquake with a magnitude of 3.6 on the Richter scale causing significant material damages marked a turning point in gas production in the Netherlands. Thereafter, in massive public protests, the inhabitants demanded the termination of the gas production from the Groningen field. They also claimed compensation for the material damages caused by the earthquakes and protection of their personal safety and health (Van de Graaff et al., 2018; Voort and Vanclay, 2015). Subsequently, to reduce the (severity of) earthquakes, the production from the field was reduced—as illustrated by Fig. 2. Yet the earthquakes continued. Early 2018 saw a new severe earthquake that eventually led the Dutch government to announce the full termination of Groningen gas production by 2030. The phasing out will be gradual, with the first significant milestone set in 2022: down from 53 billion cubic meters (BCM) in 2013, in 2022 production is aimed to be no more than 12 BCM (EZK, 2018a). The termination of Groningen-gas production will leave the Netherlands reliant on other sources of gas or energy. Part of the gas demand may be sourced from smaller gas fields in the North Sea. Although the total production of gas from these depleting fields has also dropped – from a 50 BCM peak in 2000 to 20 BCM in 2016 – they remain (The Brattle Group, 2017). In addition, gas will have to be imported. The Netherlands had already developed itself as a major trading hub for natural gas since 2004. This was initiated by the Dutch government and the gas industry to guarantee security of supply when domestic gas production gradually would decline. Moreover, it would enable the continued use and commercial exploitation of the pre-existing transport infrastructure for domestic supply and international gas transit. The conversion of depleted smaller fields and aquifers as storage facilities, the construction of an LNG terminal in Rotterdam and the development of the TTF gas whole-sale market would shift the role of the Netherlands from a mere gas producer towards a position as a main distributor of (imported) gas in the surrounding countries in North West Europe. These policies has had the intended effect of situating the Netherlands as a *gas roundabout*, thus increasing the imports and exports of H-gas in the Dutch transmission system (EZ, 2006; The Brattle Group, 2017). Importantly it currently also allows the country to substitute its use of Groningen gas with gas imported from Norway and Russia and as LNG.

The Netherlands' gas infrastructure has been shaped by the discovery of the Groningen field. Fig. 2 illustrates that the Dutch gas policy in the 1960s was initially by increasing estimates of the fields' ultimately recoverable reserves. From an initial 60 BCM in 1960 the estimates were adjusted to upwards of 1900 BCM in 1967 and even more thereafter. It was expected that that natural gas would be substituted by nuclear energy as the cheapest source of energy by the turn of the century, and the Dutch government facilitated large-scale consumption to reap the benefits of its newly found resources. Natural gas was made readily available to households and industry in the Netherlands and surrounding countries (Correljé, 2011; TNO, 2017). Domestically, Groningen gas (or G-gas) has become part and parcel of the economy.[3] Competitively priced and abundantly available, it gave an impetus to gas-fired domestic heating, cooking and hot-water provision. To illustrate, 98% of Dutch households are connected to the gas grid (Weidenaar et al., 2012). All appliances are attuned to the specific characteristics of G-gas, which has a unique composition due to the geological characteristics of the field. With approximately 14%

[2] The Netherlands is the only EU Member State that requires strict DSO ownership unbundling (CEER, 2016). DSOs are allowed, however, to engage in experiments and pre-commercial pilot projects to some extent.

[3] Natural gas accounted for 36% if total energy consumption in 2017; Oil, Coal, Nuclear and renewables accounted for respectively 48%; 9%; 1% and 5% (BP, 2019).

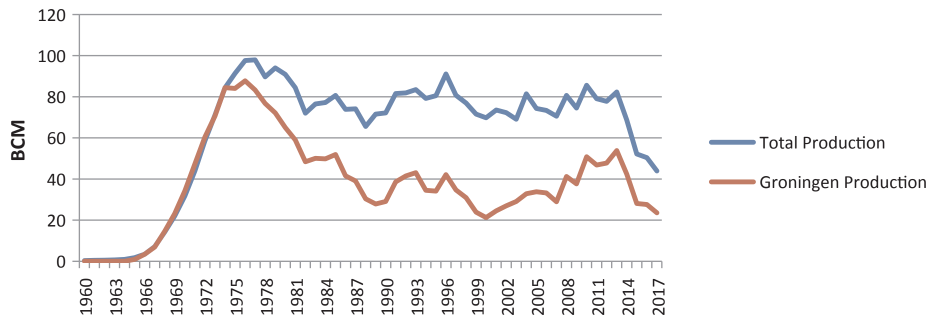

Fig. 2. Gas balance (in Billion Cubic Metres).
Source: CBS Gas Balance.

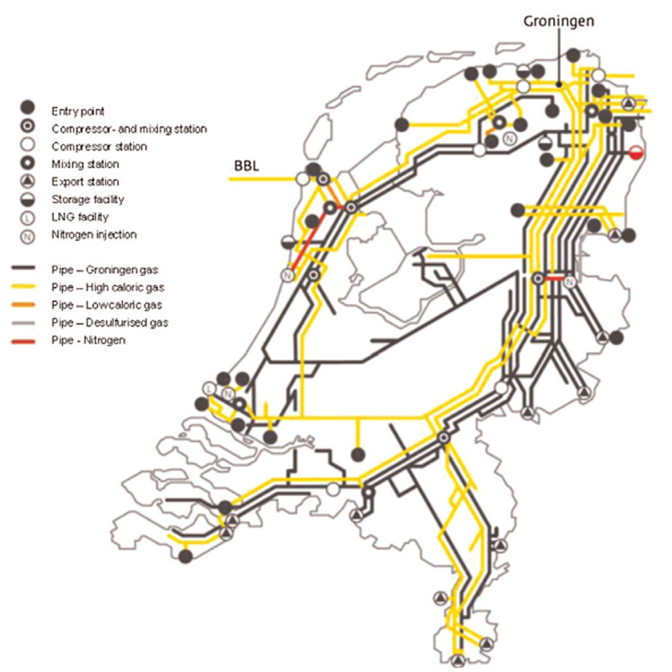

Fig. 3. Gas Transmission in the Netherlands.
Source: Gasunie Transport Services.

nitrogen, it is low in calorific value compared to high calorific gas (H-gas) that is found in the majority of the world's gas fields and commonly traded on global markets. Both gasses are not interchangeable, and devices that are designed for one type of gas cannot safely be operated with the other. When it became clear in the mid-1970s that most other gas fields in the Netherlands contained H-gas, a separate H-gas infrastructure was developed which supplies a limited number of large industrial gas users, power plants and export connections (Correljé et al., 2003). Accordingly, large parts of the Netherlands have a parallel transmission infrastructure for two separate sorts of gas (Fig. 3), while the distribution grids remain dedicated to G-gas.

3.2.2. *Implications for gas provision*

The termination of the production of Groningen gas drastically influences the future of gas provision. Appliances or industrial processes using G gas must be adjusted so they can operate with H-gas, or H-gas can be blended with nitrogen in order to create artificial, or *pseudo*, G-gas. Both options rely on the availability of H-gas, which is reflected in the rapid post 2014 increase in imports as illustrated by Fig. 4. The Dutch government encourages the retrofitting of G-gas processes for large industries currently connected to the G-gas grid. Adjusting industrial processes so that they can be operated with H-gas or alternative sources of energy must save 7.5 BCM of Groningen gas annually from 2022 onwards (EZK, 2018a). The imminent decline of G-gas production also increases the use of pseudo G-gas, which was already produced by GTS in order to maintain secure gas supply in exceptionally cold winters.[4] An additional nitrogen installation should be built by 2022 and enable the yearly conversion of about 5.5 BCM of H-gas into 7 BCM of G-gas (EZK, 2018a). H-gas conversion avoids a situation where appliances that are currently tailored to G-gas specifications need to be adjusted on short notice – something that is especially relevant for the estimated 14.4 million appliances in domestic dwellings connected to the distribution grid (Staatscourant, 2016).

Yet the prominent role of natural gas in households is also set to change. As long as imported H-gas or other gasses get converted to match G-gas quality, natural gas can still be used to provide energy. Otherwise, appliances must be recalibrated or replaced to accommodate other gas qualities. The decreasing share of domestically sourced gas is unlikely to change this in the nearby future, even though gas is expected to lose ground to other energy carriers (Netbeheer Nederland, 2017). The termination of the Groningen-gas field speeds up the process with which the usage natural gas is discouraged. The Netherlands has abolished mandatory natural gas connections for newly built dwellings and is actively supporting low-carbon sources of heating (EZK, 2018a). What source of energy will ultimately provide core functions such as heating and cooking will be coordinated on a regional level, and orchestrated primarily by municipalities and DSOs (EZK, 2018b). A situation is likely to emerge where energy provision is heterogeneous, and some parts of the network will see a substantial decline in usage, resulting in *underutilization* (Section 4.4) or even abolishment (Netbeheer Nederland, 2017). A determining factor in the determining future usage of the grid is its lifetime. A significant share of the Dutch gas (distribution) infrastructure that was constructed from the mid-1960s is due to be replaced as it approaches its 50-year technical lifetime (Weidenaar et al., 2012). Accordingly, DSOs face a complicated dilemma: they can choose to either invest in their gas infrastructure or postpone investments in anticipation of more certainty about their future purpose. For while some parts of the distribution infrastructure may be abolished and replaced by heat networks or electric solutions, other parts may need to transport gasses for another 50 years to come.

3.3. *Commitment to climate goals*

3.3.1. *Historical developments*

The Netherlands aims to reduce its CO_2 emissions to 80–95% of 1990 levels by 2050 to meet climate goals set by the 2015 Paris agreement and is expected to further substitute fossil fuels with energy from renewable sources to reach these goals (ECN, 2017; EZK, 2018b).

[4] GTS converted a total of 26.41 and 29.27BCM of H-gas to G-gas in 2016 and 2017, respectively. https://report2017.gasunie.nl/onze-resultaten/resultaten-netbeheer-nederland-en-duitsland (last accessed January 14th, 2019).

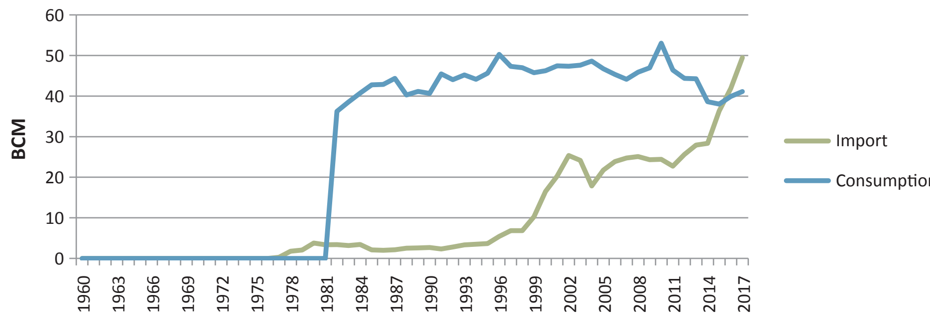

Fig. 4. Gas balance (in BCM), data for consumption starts at 1981.
Source: CBS Gas Balance.

While the overall usage of natural gas is expected to decline in the Netherlands, the hub function of the Dutch gas transmission infrastructure is unlikely to disappear in the nearby future. Across Europe, natural gas is increasingly used to substitute for coal (Stern, 2017), and the Dutch infrastructure may be used for the transmission of renewable gasses—green gas and hydrogen being most likely (Speirs et al., 2018; The Brattle Group, 2017). Green gas is derived from biomass, i.e. at agricultural sites or waste water treatment plants. It is currently the only renewable gas that is permitted in the Netherlands, but must be adapted to match quality standards of natural gas (Tempelman, 2017a). Hydrogen emits zero CO_2 during combustion, but is not renewable by default. The majority of hydrogen production today is performed by steam-methane reforming of natural gas, emitting CO_2 in the process that can potentially be stored underground. This hydrogen is called *grey* hydrogen, or *blue* when the resulting CO_2 is stored underground. Hydrogen is renewable—or *green*—when produced from renewable energy sources, for example electrolysis of green electricity. Both renewable gasses are to some extent compatible with the current Dutch infrastructure, but their use in a system designed for natural gas requires changes in the current system (Netbeheer Nederland, 2017).

As stated, the gas infrastructure in the Netherlands was largely designed for the provision of gas from the Groningen field to end-users. The gas transmission grid consists of the main transport pipelines transporting gas from gas fields, underground gas storages and import entry points to destinations across the country and abroad. Fig. 3 illustrates the transmission networks in the Netherlands, with the two colors distinguishing G-gas from H-gas networks. The (G-gas) transmission networks feed into local distribution grids at the so-called gas reception station (Dutch: *Gasoverslagstation,* GOS), where gas is distributed further under lower pressure. Gas continues through the distribution grid, as seen in Fig. 5, where it is provided to the medium-sized industrial customers or depressurized once more before it is delivered to commercial users, public buildings or domestic dwellings. While high pressure grids allow for efficient transport of gas over large distances, medium- to low-pressure grids are more suitable to transport gas through populated areas and deliver to domestic properties as well as industries. The unidirectional gas flow from gas field to transmission network to distribution network has been effective ever since the lay out of the grid after the discovery of the Groningen field, but the situation is changing.

3.3.2. Implications for gas provision

The introduction of both renewable gasses holds implications for different parts of the gas grid. The phase-out of G-gas is likely to create more capacity in parts of the grid, providing opportunities for the transmission of hydrogen (Interview 9). Initial research indicates that the transmission grid is largely amenable to hydrogen, even if compressor stations that are currently tailored to G-gas throughput would have to be replaced in order to facilitate hydrogen transmission (DNV GL, 2017). Hydrogen could be produced through large-scale electrolysis, for example from wind farms in the North Sea. In the short run, however, hydrogen produced by fossil fuel combustion is more likely as *green* hydrogen is not expected to become commercially competitive before 2030 (CE Delft, 2018a). Hydrogen may also be blended with natural gas. Currently, the maximum permitted percentage of hydrogen is 0.02% and 0.5% in the transmission- and distribution grid, respectively,[5] but research indicates that a higher percentage (up to 20%) may be possible (Kippers et al., 2011). Green gas, as it is currently produced, shares the characteristics of natural gas and can potentially be transported through the transmission grid without any adaptations. Compatibility of both renewable gasses with the current infrastructure largely depends on clear arrangements for permitted gas qualities (Section 4.1), but there are other major differences with natural gas. In the Netherlands, green gas is mostly produced in small-scale plants such as agricultural sites or waste water treatment plants. These plants are connected to the distribution network and close to the point of final consumption. Moreover, the production of green gas is a continuous process, which results in a steady inflow of gas that needs to be absorbed by local consumers throughout all seasons. Currently it is not technically possible to reverse gas flows in the opposite direction from the distribution grid back into the transmission grid. Hence, decentral produced gas cannot be transported to other regions or large-scale storage facilities. Accordingly, there is a danger of local oversupply of green gas (Section 4.3). This issue is most pressing at times when gas demand for heating purposes is low, such as throughout the summer or at night. The geographical distribution of available biomass from which green gas can be produced makes this matter even more urgent. Rural areas in the North, East and South of the Netherlands have the highest potential for the production of biogas and green gas, but often have relatively low gas demand (AT Osborne, 2016; Netbeheer Nederland, 2018b). Hydrogen may pose similar challenges, as will be further explored in Section 4.

4. Safety concerns in Dutch gas provision

The historical developments covered in the previous section challenges safety in a number of ways. In this section, we elaborate four safety concerns: (1) non-standardized gas quality; (2) inadequate gas appliances; (3) loss of system control; (4) underutilization. Each concern is illustrated by first outlining existing safety practices. These are activities aimed at mitigating risk, including *passive* controls (i.e. that function automatically by their presence, such as pressure relief vaults) as well as *active* controls (i.e. that require a further activity to maintain safety, such as the detection of a gas leak) (Christensen et al., 2003; Leveson, 2011, pp. 76–77). We then show how existing safety practices are influenced by ongoing developments, touching on issues related to risks and hazards. Risks are generally understood as the combination of the severity and likelihood of an accident or loss and, thus, expressed as

[5] https://wetten.overheid.nl/BWBR0035367/2016–04-01 (accessed December 4th, 2018).

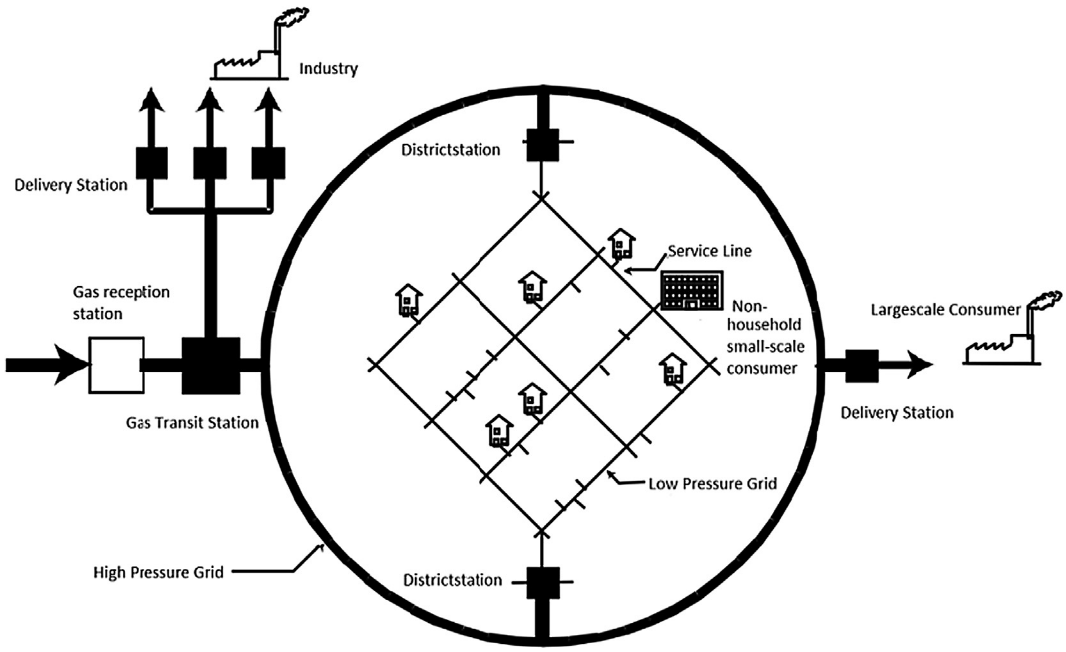

Fig. 5. Gas Distribution Network in the Netherlands.
Source: Adapted from (Netbeheer Nederland, 2016).

a number. Hazards indicate a set of conditions that may lead to an accident or loss and are thus more specific (Leveson, 2011). We do not quantify risk, acknowledging that estimations associated with new technological solutions may produce misguided conclusions. Instead, we identify *risk factors*, factors that alone or in combination may lead to an accident (Christensen et al., 2003; Leveson, 2011). Risk factors are defined broadly as "factors leading to an accident" (Leveson, 2011, p. 467), and deliberately include hazards (i.e. the presence of gas in an enclosed space), as well as the conditions that may turn the hazard into an accident (i.e. failure to install proper gas detection mechanisms). We refer to a hazard profile, then, as a comprehensive overview of relevant safety concerns—in our case pertaining to a changing gas sector in the Netherlands. An illustrative overview and outcome of this section is presented in the discussion.

4.1. Non-standardized gas quality

4.1.1. Existing safety practices

In order to safely combust and transport gas, appliances and pipelines must have appropriately designed features. Depending on the physical composition of the gas, appliances need a compatible type of burner. The degree with which hydrogen and hydrocarbons such as ethane and propane are present in natural gas, for example, relates to soot formation as well as the flame stability and velocity (Jepma and Rop, 2013; Netbeheer Nederland, 2016). Soot is a toxic substance, and inhaling it may cause damage to lungs; a lack of flame stability or instable flame velocity can be associated with incomplete combustion and related dangers of intoxication and explosion. Attuning burner design to gas quality are two safety practices to mitigate these dangers. Other safety practices relate to pipelines. A large-scale replacement program is underway that substitutes grey cast-iron mains with polyethylene pipelines. The latter are less prone to leakage, and are compatible with renewable gasses (Brouns and Poorts, 2012). One of the ways in which gas quality is measured is by the Wobbe index—an index that relates to the calorific or energy content and the density of a gas. The Wobbe index is important for determining the interchangeability of different gasses, but other important parameters include the share of H_2 and liquids in the gas (Jepma and Rop, 2013). Gas odorization is a safety practice that requires further action to mitigate accidents. Natural gas is generally odorless, and it has become common practice to add THT, giving the gas a specific smell in order to enable identification of gas leaks (Van der Wal, 2013). Timely identification of a gas leak can avoid major injuries or accidents, but adding the particular gas smell to green gas and hydrogen proves difficult.

4.1.2. Risk factors influencing safety practices

The rapid phasing out of G-gas production complicates current gas quality standards. A significant part of the Dutch gas grid, including the entire distribution segment, is designed for operating G-gas quality. The *decreased use of G-gas* will be matched by an *increased use of H-gas* and other *gasses with different characteristics*. Only green gas matches G-gas specifications and can be safely transported and combusted. Other gasses raise safety issues (Interview 11). High calorific gasses from imports and domestic production have a higher Wobbe-index, and combustion with appliances attuned to G-gas characteristics may cause ignition problems or toxic emissions. Biogas (i.e. gasses derived from biomass that do not match green gas specifications) contains varying amounts of moisture, which may cause leakage due to corrosion in pipelines and fittings. Unlike natural gas, biogas has a moisture content that is higher than that of air. Potential explosions would produce horizontally spreading flames, causing significantly more damage to the immediate surroundings than vertically spreading flames of natural gas (Interview 8). At the same time, however, biogas contains less methane than natural gas, reducing the amount of heat produced during an explosion. Depending on its origin, biogas might also contain toxic elements that are more harmful than those of natural gas to people who are close to a gas leak (RVO, 2016). Hydrogen has explosion and combustion properties that are entirely different from natural gas or biogas. It ignites and explodes more easily, requiring different safety precautions. Yet its low density makes it evaporate into air relatively easy, limiting the size of hazardous hydrogen clouds. Much is yet unclear about leakage behavior of hydrogen, especially indoors. While hydrogen can be transported through (the majority of) existing pipelines, its use requires significant investments as appliances must be replaced or upgraded for safe combustion (KIWA, 2018a). Finally, both the increased use of biogas and hydrogen influence the odorization safety practice. Certain trace components in biogas can mask the typical gas smell added by the substance THT (Interview 8). This causes hazardous situations in case of leakage or malfunctioning appliances (RVO, 2016). THT cannot be applied to hydrogen for odorization, as it compromises the quality of fuel cells, which are a key hydrogen technology that require very pure hydrogen for combustion. Accordingly, there is a need for a different odorant that yields the familiar and recognizable gas smell (KIWA, 2018a).

4.1.3. Changing hazard profile

The safety practices that are currently in place are not adequate to deal with increasingly diverse gas quality. The decline in the use of G-gas renders safety issues pertaining to H-gas most urgent, while those related to renewable gasses are expected to become more relevant over time. The hazard profile remains unchanged as long as (imported) H-gas is treated to match G-gas specifications Yet it will change substantially because of the different properties of alternatives for G-gas. Odorization issues related to renewable gasses impede awareness of gas leaks, especially for hydrogen. Different explosion characteristics have significant implications for safety protocols for not only system operators, but also emergency services more generally. Large-scale retrofitting efforts will be required to effectively mitigate fires and explosions induced by biogas and hydrogen (KIWA, 2018a). Changing to H-gas or renewable gasses may also require large-scale appliance upgrading or replacement efforts, as was the case in Britain and the Netherlands in the 1960s and 1970s (Arapostathis et al., 2019b) and currently seen in Belgium (Vlaanderen, n.d.). *Non-standardized gas quality* and *inadequate appliances* are two sides of the same hazard coin, as is explained below.

4.2. Inadequate appliances

4.2.1. Current safety practices

Carbon monoxide (CO) release is the most lethal gas hazard in the Netherlands, with an estimated five to ten fatal accidents per year (Onderzoeksraad voor Veiligheid, 2015). Safe and well maintained appliances are key to minimizing this hazard (Interview 6). Accordingly, the way in which these appliances are inspected, and who is responsible for their maintenance, are crucial institutional arrangements to secure domestic gas safety. Prior to the liberalization of the Dutch gas sector, quality checks for appliances and their fitting and installation were obligatory under the authority of the local gas utility. As the consequence of restructuring, roles and responsibilities regarding domestic use were re-allocated—resulting in more lenient safety practices. Importantly, a legal distinction is made between responsibility for safety *before* and *behind* the gas meter. The former pertains the part of the infrastructure providing gas to users which remained under control of the DSO. The latter comprises in-house piping and appliances and has undergone significant changes, as the following will show.

4.2.2. Risk factors influencing safety practices

Risk factors for domestic safety, i.e. *behind* the gas meter, are related to four safety practices:

- Requirements to register accidents;
- Provision of quality checks for appliances;
- Certification of installers; and
- Supervision of installers.

There is no obligation to report or register domestic gas accidents in the Netherlands, although yearly reports are drawn up that analyze known instances (KIWA, 2018b, 2016). Up until the 1990s, these reports were often compiled by data from registered gas installers employed by the local public utilities. This registration scheme was abolished in the course of liberalization. Alternatively, data is now gathered through more indirect means such as newspaper analysis and, later, online publications. These reports show an increase in both accidental and deliberate yearly fatalities related to natural gas consumption (primarily caused by CO-poisoning) in the first years after liberalization, peaking in 2003. While fatalities have gone down since then, there is no clearly distinguishable pattern. Inspections are currently obligatory only for appliances with a total capacity of above 100 kW; inspections for appliances below this threshold are voluntary. To illustrate, a stand-alone house requires a gas-fired boiler of approximately 30 kW for heating, with the majority of houses requiring less.[6] Installers who provide quality checks for appliances can operate without certification; they can choose to get certification under quality labels that have been established by the installation branch or choose to operate without. The latter option avoids costs of schooling and certification of staff, allowing them to offer their services at lower prices (Onderzoeksraad voor Veiligheid, 2015). The legal responsibility for monitoring residential safety, including the work of installation companies, has shifted from the gas utility to the municipalities governments. However, partly due to a lack of technical expertise, the supervision tasks are effectively limited to newly built dwellings and those under reconstruction. As a consequence, the privately initiated quality labels are the main institutional arrangements for providing safety behind the meter. Given the differences between these labels and the fact that installers can choose among a number of labels, this has led to ambivalence regarding the actual quality these labels provide (Ecorys and Senze, 2014; Onderzoeksraad voor Veiligheid, 2015).

4.2.3. Changing hazard profile

An increasingly heterogeneous supply of gasses amplifies hazards related to *inadequate gas appliances*. Section 4.1 explained how faulty gas combustion may cause lethal accidents; the current section explored how mitigation of these accidents is organized. The four highlighted aspects show that liberalization was followed by an increased focus on market instruments and *voluntary quality checks* and certification (Interviews 1, 7). Comparing these results to neighboring countries that underwent a similar process of liberalization yields the comparison shown in Table 1. DSOs remain important actors in supervising gas appliances in nearby countries, with registration of gas accidents and certification of installers often required. The viability of current safety practices merits research as the technical features of gas combustion change rapidly, raising concerns about *appliance compatibility with H-gas and renewable gasses*. Recently, the Dutch authorities approved to re-install certification and supervision requirements for gas installers.[7] From 2021 onwards, the liability for domestic safety resides with the building contractor. Registration of accidents and quality checks for existing appliances remain voluntary.

4.3. Loss of system control

4.3.1. Current safety practices

The continued safe supply of gas relies on a number of functions such as balancing, storage and quality control. As we established in the previous chapter (Section 3.1), these functions were traditionally executed by Gasunie. Its subsidiary GTS still plays a major role in monitoring and controlling these functions even though other actors gain importance. In particular, the way in which green gas is produced defies conventional practices of quality control and grid balancing. While the TSO checks the quality of natural gas in the transmission segment of the grid, green gas producers are individually responsible for upgrading their biogas to match requirements for entry in the distribution segment. The DSOs provide periodic checks on the gas that is produced, and are able to close off gas entry from their control room should any crucial specifications be off-limit. DSOs become responsible for the quality of green gas once it enters the (distribution) grid (AT Osborne,

[6] Data from https://www.feenstra.com/cv-ketel/info/vermogen/.

[7] https://www.rijksoverheid.nl/onderwerpen/bouwregelgeving/plannen-kabinet-voor-meer-toezicht-in-de-bouw (last accessed June 6th, 2019).

Table 1
Supervision of gas appliances in the Netherlands compared to neighboring countries.
Source: Adapted from Onderzoeksraad voor Veiligheid (2015).

	Registration	Quality check	Certification	Supervision
The Netherlands	None	> 100 kW	Not required	None required
Germany	Accidents and defects	Installing, revision and replacing	Required	DSO/Chimney sweeper
Belgium	Accidents	Periodic maintenance	Required for gas connection	DSO
Great Britain	Accidents and defects	Yearly check and required maintenance in rental properties	Required	Health and Safety Executive, Gas Safe register
Denmark	Unknown	Required maintenance 1–2 year	Required	DSO

2016; Tempelman, 2017b). Current safety practices already respond to the trend of decentralization and are very different from a decade ago. Yet, new risk factors are emerging.

4.3.2. Risk factors influencing safety practices

The current scale of injection of green gas in Dutch gas networks has caused no significant safety concerns (Interviews 3, 10). However, the expected increase of renewable—including green—gas production may change this. The growing use of G-gas alternatives poses a potential threat for a continuous safe production of gas, as regulators need to supervise an increasing amount of production facilities and related technologies (Toezine, 2019, Interview 5). The decentralization of safety responsibilities creates a risk factor in this respect, especially since many new gas producers do not have experience with gas production. Producers of green gas, for example, increasingly produce as a new branch in an already existing business, such as waste management and farming. *Insufficient regulatory capacity* and/or information asymmetries between the regulator and producer of renewable gas may result in gas production facilities that do not match required safety standards, leading to hazards that were explored at length in Section 4.1.

4.3.3. Changing hazard profile

Key roles in maintaining gas safety in the Netherlands are thus increasingly located in the distribution segment of the grid. In the case of green gas production this follows from a focus on *individual* rather than *collective* biogas (and by consequence, green gas) plants.[8] While in an individual plant the producer of biogas performs the upgrading to green gas himself, collective plants bundle supply from multiple producers of biogas and centralize the upgrading process. Other countries, for example Denmark, have adopted *centralized* biogas plants to reduce production costs (Raven and Geels, 2010). Unlike in the Netherlands, the centralized plants in Denmark are equipped to inject green gas directly into the transmission network, thereby also mitigating problems of congestion and storage in the distribution grid (Aryal and Kvist, 2018). The two green gas production methods differ significantly in respect of their technical characteristics and, consequently, also in their organization. While Denmark assigns the juridical responsibility for safe green gas production to a handful of centralized production firms that service the transmission segment, the Dutch case is characterized by a *decentral production* that focuses on individual producers injecting into the distribution grids (CE Delft, 2018b; Raven and Geels, 2010). Accordingly, the *increased dependence on G-gas alternatives*—including green gas—is likely to make the role of regionally operating parties such as DSOs and municipalities more important in guaranteeing safe and continuous gas supply.

[8] Collective biogas upgrading facilities exist also in the Netherlands, for example in the north-eastern village of Wijster. The Netherlands' first green gas injection facility for the transmission grid will be realized here in 2019. https://www.gasunie.nl/nieuws/start-aanleg-groen-gas-booster (accessed January 17th, 2019).

4.4. Underutilization

4.4.1. Current safety practices

The regulated gas network was initially designed as a large-scale technical system providing natural gas as a public service. It still functions as a regulated monopoly, where publicly owned operators are able to realize increasing returns of scale and reduced costs per connection as the network expands. Apart from these networks, however, privately owned and operated networks exist. These private networks come in many sizes: from serving Schiphol International Airport to vacation parks and residential areas. Responsibilities for these private networks related to maintenance and safety are unclear, sometimes causing hazardous situations (Interview 4; Energeia, 2014, 2015). Regulatory authorities gained more controlling powers with regards to the supervision over these networks in 2018, but problems remain (SODM, 2019). The position of both publicly *and* privately owned networks is set to change as natural gas loses prominence.

4.4.2. Risk factors influencing safety practices

Section 3 illustrated how the use of natural gas is actively discouraged. A situation is likely to emerge where parts of the infrastructure are used to transport renewable gasses, while other parts may be abolished. It is unlikely that the current capacity of the Dutch gas infrastructure will be fully used, leading to safety concerns associated with *underutilization* (Interviews 1, 12). There are two major issues. First, decreasing utilization lowers *system operators' revenue*. Network tariffs may have to increase to offset revenues lost from customers being disconnected or disconnecting from the grid. As a consequence, this may provide even stronger financial incentives to disconnect from the grid, resulting in a spiral of decreasing gas consumption and increasing service costs. Lower revenues for the system operators puts a strain on spending, potentially causing hazardous situations associated with inadequate maintenance. Second, decreasing coverage of a publicly operated gas grid may spur *privately owned and operated gas grids* to service *isolated communities*. In areas that are not—or no longer—connected to the gas network, privately owned and operated gas infrastructure and combustion devices may evolve. This is already a known problem in some areas that have been connected to heat networks. Unregistered gas devices, like butane and propane fueled stoves, barbeques, oven burners and terrace heaters are privately operated. They are not subject to licensing, and may be stored and used under hazardous circumstances, for example on apartment complex balconies (Interview 12).

4.4.3. Changing hazard profile

There is little academic and practical experience with downsizing large infrastructures. Moss describes effects of rising utility prices in the context of underutilization in his study of water infrastructure in Eastern Germany after reunification. Water prices rose to such an extent that the consumers disconnected from the public infrastructure, and resorted to alternatives such as the usage of water-wells in gardens (Correljé and Schuetze, 2012; Moss, 2008). These alternatives place water provision outside the scope of regulators, allowing for consumption of water that does not meet required safety standards. Similar trends in Dutch gas provision could spur unregistered gas devices, such

Table 2
Unravelling safety concerns in Dutch gas provision. Bold cells indicate direct relation to distribution segment.

	Historical Developments		
Safety concerns	Liberalization	Earthquakes	Climate Goals
Non-standardized gas quality	Increased H-gas use (Section 3.1)	Decreased G-gas use (Section 3.2)	**Different gas characteristics (Section 4.1)**
Inadequate appliances	**Voluntary quality checks (Section 4.2)**	**Appliance compatibility H-gas (Section 4.2)**	**Appliance compatibility renewable gasses (Section 4.2)**
Loss of System Control	**Insufficient regulatory capacity (Section 3.1)**	**Increased dependence non G-gas (Sections 3.2 and 3.3)**	**Decentral production (Section 4.3)**
Underutilization	**Privately operated gas combustion (Section 4.4)**	**Decreasing revenue system operators (Section 4.4)**	**Isolated grids of renewable gasses (Section 4.4)**

as observed above, but also privately operated grids providing renewable gasses on a local scale. For example, local communities might use excess renewable electricity for producing hydrogen gas and distributing it in a local grid. The prospect of an increasingly scattered and heterogeneous gas grid involves a variety of safety concerns and casts doubt on the viability of current safety practices.

5. Discussion and conclusions

We identified four safety concerns that follow from historical developments in the Dutch gas sector. Table 2 illustrates twelve risk factors that link these together, and shows how different developments combine to influence the same safety concerns. Safety hazards related to non-standardized gas quality, for example, are induced by a reduced production of G-gas, combined with a growing presence of alternatives, both natural and renewable gasses with different characteristics. While safe transport and combustion of these substitutes is relatively straightforward, both technical and institutional features of the gas sector prevent a fast and safe transition. Even if much of the infrastructure is suitable for transporting alternative gasses, safe combustion hinges on their compatibility with appliances and installations. Mitigating (future) hazards related to gas quality, such as the inadvertent release of carbon monoxide, relies as much on the technical characteristics of the network as on the institutional arrangements in place to guarantee safe operation.

Against the backdrop of a liberalized sector, new gasses, technologies and political ambitions have set the scene for increasingly decentral and regional governance of safety. We identified risk factors related to the increasingly fragmented regulation and supervision for domestic safety, as well as for potential future grid supervision and maintenance. Decentralizing control for domestic safety went hand-in-hand with an increased reliance on market instruments and voluntary quality checks. Without implying causality between these new institutional arrangements and gas accidents, several high-profile cases of CO-poisoning have rekindled the debate concerning the preferred role of private involvement in providing safety. This debate must be revisited when discussing options for mitigating risks associated with increasing decentral supply of gas. Private provision of natural and renewable gas prompts safety concerns in the context of underutilization; these manifest themselves in domestic environments or in larger networks exempt from regulatory scrutiny, including the usage of gas cylinders in unsafe environments and private gas grids in bad repair. The growth of green gas production, and especially an impending hydrogen infrastructure calls for effective governance arrangements that carefully allocate safety responsibilities across different actors—both private and public. Experience with domestic green gas provision can provide important insights in this respect and nearby countries such as Denmark have also shown strategies that could be considered.

The identified safety concerns fill a gap in existing academic and technical literature. By situating them in their wider context we find a number of trends that hold significant implications for safety governance. Fragmentation of roles and responsibilities regarding gas safety, combined with technical and institutional decentralization, creates substantial new hazards and influences existing ones. We also observe a strong focus on the distribution segment of the grid: out of twelve identified risk factors that are shown in Table 2, ten (shaded) cells apply directly to this part. The increasing importance of the distribution segment of the grid contrasts with prevailing safety practices. Current arrangements are based on a grid use that is increasingly subject to change, and we expect a more significant role for actors associated with the distribution segment such as municipalities, renewable gas producers and DSOs. The increasing number of actors also warrants a wider mandate for regulators. Further research should investigate preferred modes of governance that can effectively control safety in the changing gas sector. This paper provides a first step to this end, but also carries wider implications for energy systems and other infrastructures.

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Appendix A. Interviews

1.	15-03-2017	DSO	Asset manager
2.	19-03-2017	DSO	Safety director
3.	20-03-2017	DSO	Asset manager
4.	30-03-2017	Regulator	Legal counsel
5.	31-03-2017	Regulator	Inspector (2x)
6.	07-04-2017	Certification institute	Consultant (2x)
7.	05-02-2018	DSO	Program manager
8.	15-03-2018	DSO	Asset manager
9.	23-03-2018	TSO	Advisor infrastructure
10.	29-03-2018	Renewable gas producer	Board member
11.	05-04-2018	Certification institute	Consultant
12.	24-01-2019	DSO	Asset manager

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