Chapter 7
The Groningen Gas Field: The Role of Science in a Slow-Onset Disaster

Tom Postmes, Nienke Busscher, Sanne Hupkes, Agustín De Julio, and Ena Vojvodic

Abstract This chapter presents a case study of the Groningen gas field. We study the role of science and knowledge in the assessment, monitoring and management of escalating earthquake risks. The case is relevant to climate change in several ways. Around 2006, gas extraction from Groningen was increased with the narrative that gas was the "ideal energy transition fuel". Gas is more climate-friendly than burning coal or oil, and gas-fueled power plants combine well with renewables (Heath et al. in Proc. Natl. Acad. Sci. 111(31):E3167–E3176, 2014). Much less attention was devoted to known risks: subsidence, pollution and earthquakes. The latter caused a slow-onset disaster in Groningen. Lessons from this case are relevant to renewable energy initiatives such as hydrogen storage and geothermal energy, as well as to the future exploitations of gas fields, made more likely by the Ukraine war. At the end of the chapter, we reflect on governance of big industrial risks amid climate change.

Keywords Energy · Induced earthquakes · Slow-onset disaster · Risk science

7.1 The Groningen Case: An Overview

The Groningen field in the Netherlands is one of the largest in the world; 20% of its 2800 million m^3 remains (Muntendam-Bos et al. 2022). It was exploited by the *Gasgebouw* (literally: gas building), a public–private partnership. The *Gasgebouw* contains multiple legal entities, which function as a joint enterprise of the Ministry of Economic Affairs (representing the State) and oil companies. To the outside world, the state appears independent of the operator NAM and its shareholders (Shell and Exxon). But the partners in the *Gasgebouw* made strategic decisions jointly until around 2018. Production began in 1963. Gas sold in Northern Europe and Italy totaled €428 billion up to 2022, with 85% going to the state (Fig. 7.1a) (Been 2022). In economic terms, this was an extraordinary success, but it became a "disaster in slow motion" (Parlementaire enquêtecommissie aardgaswinning Groningen

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C. Bieder et al. (eds.), *Climate Change and Safety in High-Risk Industries*,
SpringerBriefs in Safety Management, https://doi.org/10.1007/978-3-031-56995-1_7

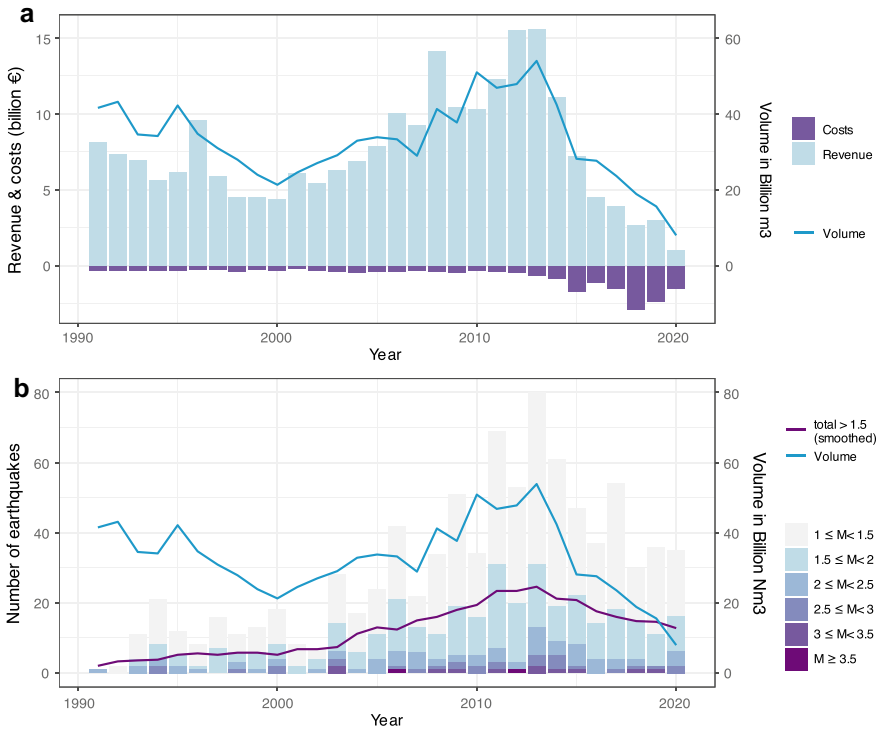

Fig. 7.1 **a** Revenue and costs from the Groningen field, at 2020 price levels. The blue line shows the annual gas production in billion cubic meters (bcm). Drawn from data derived from Been (2022). **b** Evolution of seismicity in Groningen. The bars show the annual number of earthquakes in different magnitude classes. The dark line shows the 5-year moving average of annual $M \geq 1.5$ events. Drawn from data derived from Muntendam-Bos et al. (2022), released under a CC BY 4.0 license[1]

2023). This was investigated by a parliamentary inquiry in a 1956-page report with a detailed historical account and English translation of conclusions (Parlementaire enquêtecommissie aardgaswinning Groningen 2023).

From the outset, there were known risks. One was soil subsidence—a major risk in a river delta. Publicly it was denied this could occur, even though research into it began in 1963. Only in 1972 was this risk publicly acknowledged: subsidence would be "even and limited". In the decades following, estimates ranged from 0.27 to 1 m, with revisions both downward and upward but always with small error margins, projecting certainty and confidence. Unknown to the public was that estimates ranged from 0.5 to 2.5 m in 1969. Later predictions converged, but as late as 1989 an internal review concluded that measurements and predictions still deviated for reasons unknown.

[1] The data from which this graph is derived is published under the terms of the Creative Commons Attribution license.

The operator promised the regulator to "again delve into the theoretical foundation of the model" (Parlementaire enquêtecommissie aardgaswinning Groningen 2023).

Another known risk was pollution. Gas is separated from by-products that are condensed into a toxic and explosive liquid. A tank of condensate exploded (2005), and 30 m^3 of it spilled into a canal (2018). Investigators questioned safety management and safety culture (Parlementaire enquêtecommissie aardgaswinning Groningen 2023; Staatstoezicht op de Mijnen 2019).

A third risk was initially ignored entirely: induced earthquakes. Tremors were felt already in the 1970s, but there were no seismometers and no follow-up. Installation of seismometers led to registration of numerous small earthquakes from the 1990s onward. In 1993, a large research project in which scientists collaborated with both operator and regulator concluded that these were not hazardous: they were small and would remain so. This consensus remained intact for two decades (Parlementaire enquêtecommissie aardgaswinning Groningen 2023).

In 2003 and 2006 (Fig. 7.1b), earthquakes of magnitude 3–3.5 caused widespread damage. These facts were not made public at the time. The outward appearance of consensus was maintained, but behind closed doors a few individuals raised questions. Similar magnitude earthquakes in a small field would have led to precautionary shutdown, but in Groningen production went up. Publicly, the Groningen gas was marketed as "the ideal transition fuel", because other fuels were more polluting. But the inquiry revealed that the real motive of the *Gasgebouw* was to maximize profit (Parlementaire enquêtecommissie aardgaswinning Groningen 2023).

A 3.6M earthquake in 2012 became a turning point. The regulator in 2013 called for production to be reduced "as fast as possible and as much as realistically possible". This was triggered by a site visit: the regulator noticed the extent of residents' fear and independently re-assessed risks. After a few weeks of research, they showed that the consensus was flawed: the frequency and magnitude of earthquakes were not stable, as was assumed, but increased the more gas was extracted (Parlementaire enquêtecommissie aardgaswinning Groningen 2023).

The appreciation of risks involved also gradually changed. In the 10 weeks after the M3.6 earthquake, 1937 claims were filed. This showed that widespread damage could occur, contradicting the narrative that damage would be limited and small (Parlementaire enquêtecommissie aardgaswinning Groningen 2023). Nevertheless, the *Gasgebouw* continued to treat damage as only a nuisance, not as a hazard. We shall argue below that this was a major mistake of risk management.

Another novelty was that induced earthquakes in Groningen cause more ground motion than tectonic earthquakes of a similar magnitude. Groningen earthquakes occur at a shallower depth than most tectonic earthquakes: they hit a small area hard. And yet the area affected can be unusually large: earthquakes of M3.4 can be felt up to 25 km away (Postmes et al. 2018a). The current reasoning behind this is that the top layer consists of several meters of clay or peat: wet substances that absorb the energy of the shockwave and cause tsunami-like waves that form complex patterns of direct and indirect (refracted) waves (den Bezemer and van Elk 2018).

In sum, there were alarming signs: risks were larger and more diverse than assumed. But no new consensus was reached: the next decade, operating company,

regulator and scientists would disagree about the magnitude of risks and the best way to mitigate. The regulator's recommendation to reduce production was not followed (Parlementaire enquêtecommissie aardgaswinning Groningen 2023). Instead, the operator launched a major research program. As this research was ongoing, *more* gas was extracted in 2013 and production remained high in 2014. Court rulings eventually forced the *Gasgebouw* to reduce production because it had taken insufficient account of residents' risks. The oil companies involved changed direction only when the Public Prosecution Service investigated their liability for criminal prosecution. In 2018, the government made a sudden U-turn and decided to shut down the field (now foreseen in 2023/4) (Parlementaire enquêtecommissie aardgaswinning Groningen 2023).

The initial mitigation focused on the risk of collapse. In order for production to remain high, it was announced in 2014 that buildings would be made safe again: 8000 would be reinforced over the next two years. This proved wildly optimistic and extremely costly. Until 2023, just 3326 were reinforced. The total number necessary has reduced a lot because of the decision to end extraction, but because earthquakes will continue for at least a decade, a further 14,000 still need doing (Parlementaire enquêtecommissie aardgaswinning Groningen 2023). Reinforcement ended up being a completely ineffective mitigation strategy (Sintubin 2018; Vlek 2018).

Over the years, there were 267,466 damage claims. Around 85,000 addresses had damage repeatedly. The operator argued that since most damage was relatively small, it is a nuisance and not hazardous. Accordingly, their risk assessment ignored it. Moreover, damage claim handling became a major source of conflict: claims were often disputed, and repairs were cosmetic. The inquiry points out that some damage is more major. In fact, over the years 675 homes were declared acutely unsafe, resulting in emergency measures and/or immediate evacuation of residents. Moreover, the report concludes there is a "structural reluctance to acknowledge damages and to pay compensation. The matters often proceed at a painfully slow pace" (p. 24) (Parlementaire enquêtecommissie aardgaswinning Groningen 2023). Below, we shall argue that this structural reluctance and lack of urgency meant that even minor earthquake damage became hazardous.

7.2 Perspectives on Risk

To analyze how risks were mismanaged, we begin by considering perceptions of risk by the *Gasgebouw* and by residents, before integrating them.

7.2.1 The Gasgebouw's Perspective

The Dutch mining law states that the operator ensures that mining is safe, prevents negative impacts for people and the environment and prevents damage (Dutch Mining

Law, art. 33). In practice, however, the Gasgebouw decided to focus risk assessment and risk management entirely on *physical safety*. Damage and other negative impacts were considered a nuisance, and no boundaries or norms were established for it.

To assess physical safety, the Gasgebouw chose to make a rational scientific assessment of the risk of catastrophic earthquakes. For this, seismic risk had to be established in conjunction with structural safety of buildings (Sintubin 2018). When earthquakes were first detected in the 1990s, the scientific consensus was that seismic risk was negligible. When the regulator punctured this consensus in 2012, it became clear that risks were under-researched and under-legislated. Not only were risks uncertain and unknown (see above), an entirely new approach to risk assessment and management had to be developed. A government-established committee advised that it was best to adopt an exact scientific approach to assessing risks. It set the boundary norm of collapse leading to loss of life at $< 10^{-5}$ per year: each building had to be so solid that less than one life would be lost in 100,000 years.

The feasibility of this approach, given the uncertainties surrounding seismic risk and building safety, was questionable. Also, the norm for other industrial hazards in the Netherlands is $< 10^{-6}$ per year. The new norm also ignored the safety board's advice that "it matters that residents of Groningen are safe and feel safe in their daily environment" (p. 15) (Onderzoeksraad voor Veiligheid 2015). It took until 2018, after the decision to reduce extraction to zero, for the government to incorporate societal consequences like delays in damage repairs, health effects and social unrest into legislation. Until then, risk assessment and mitigation revolved entirely around the physical safety of *buildings*.

7.2.2 Risks from Residents' Perspective

From 2016 onward, a large-scale research project studied residents' perspectives and experiences (see www.groningsperspectief.nl). It combines qualitative data with large surveys and panel data. Representative groups of residents exposed to earthquakes are compared with control groups. The central findings are that residents who experience earthquakes and who have damage (a) feel unsafe in their homes and (b) that those who have damage multiple times experience chronic stress symptoms and have poorer mental and perceived general health (Postmes et al. 2017, 2018a; Stroebe et al. 2021; Dückers et al. 2023). The research shows that perceived unsafety mediates these health effects. Other factors such as injustice and a lack of trust in government also play a (small) role in the experienced unsafety (Fig. 7.2).

In this research, perceived unsafety is very strongly associated with concrete risk perceptions, including the likelihood of experiencing an earthquake in the future, the likelihood of one's property being damaged and the likelihood of physical injury. Perceived risk is influenced by two factors in particular: earthquake damage and seismicity. Earthquake damage has a *long-term* effect on risk perception and safety: of the people who have no damage, 85% feel safe in their home (and in the control group outside the earthquake zone this is > 90%). Among people whose house was

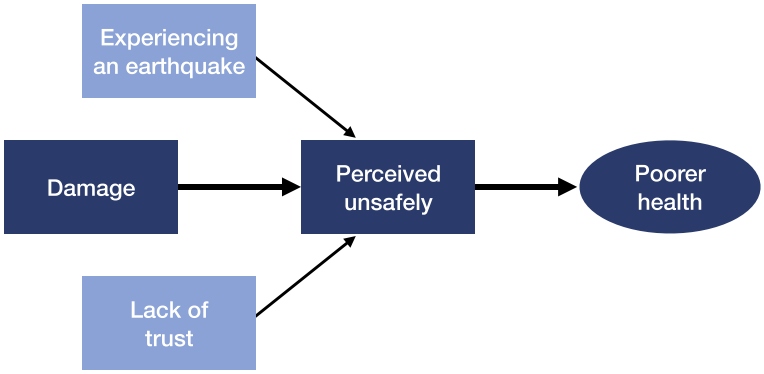

Fig. 7.2 Illustration of the relationship between exposure to earthquakes and damage, perceived trust, perceived unsafety and health outcomes in statistical path analyses (Stroebe et al. 2021)

damaged once this drops to 69%. Of those whose house was damaged multiple times, only 48% feel safe. Experiencing the ground motion of an earthquake is the second factor. Its impact is more *short term.* After experiencing a 3.4M earthquake, the percentage who feel safe in their homes drops by about 15–20%. After this dip, safety perceptions slowly recover over a period of 6–12 months (Postmes et al. 2018b).

It is also important to know what makes residents feel unsafe. We examined this in in-depth qualitative research (open-ended survey questions, interviews) and quantitative research (Postmes et al. 2018a; Stroebe et al. 2021). Residents feel unsafe mainly because of (a) the seismicity itself, (b) the recurring and widespread damage, (c) the uncertainty and lack of clarity about mitigation and repair and (d) the hassles over damage and compensation. Only 12% of residents feel unsafe because they might get hurt or because a catastrophic event may occur.

7.2.3 Integration: The Social Impact of Small Hazards

In Groningen, experts restricted their risk assessment to the big risks of a catastrophic earthquake. Residents are more concerned about smaller hazards. Small hazards can be disastrous when they are uncontrolled and large numbers are affected. Based on insights from psychological, health, economic, legal and other literatures, we outline the current state of knowledge (Hupkes et al. 2021).

Small recurrent damage is impactful and hazardous. Damage erodes people's confidence in their home because it demonstrates vulnerability to frequent and recurring earthquakes. The settlement of damage claims was inadequate due to disputes over claims, cosmetic repairs and neglect of structural faults. People with complex damage trajectories (most likely > 10,000 households) often faced lengthy bureaucratic and legal wrangling. Our research showed that around 20% of residents stopped

claiming altogether. This is problematic because small damage can accumulate and cause or exacerbate structural faults. In sum, recurrent damage is impactful because it puts people's lives on hold, curtails freedoms and threatens livelihoods.

Mitigation measures to restore physical safety are a burden for residents (Postmes et al. 2018a; Dückers et al. 2023). Uncertainties about seismic risk and structural safety caused continuous disputes about the amount of reinforcement required. As a result, residents were kept in uncertainty for many years. Once building work starts, the process is arduous. Residents did not choose to have building work done: it is forced upon them. But they still have to invest large amounts of time and energy (and sometimes money). The trajectory is prone to conflicts between the many parties involved. Moving into a temporary home is stressful too and disrupts social ties. For all these reasons, subjective safety *declines* during the reinforcement operation (Dückers et al. 2023). In sum, mitigation has a substantial negative impact.

Trust in institutions has been damaged in this "unprecedented system failure by public as well as private parties who failed in the execution of their duty" (Parlementaire enquêtecommissie aardgaswinning Groningen 2023). Relations are damaged (Hupkes et al. 2021). The first victim was residents' trust in government, the operator and its shareholders. The Gasgebouw broke down: oil companies and the government are in arbitration. And local and national governments hold each other responsible and disagree about solutions (Parlementaire enquêtecommissie aardgaswinning Groningen 2023; Stroebe et al. 2021).

This undermines trust in the responsible institutions and the system: competence is in doubt, but also morality (Parlementaire enquêtecommissie aardgaswinning Groningen 2023; Hupkes et al. 2021). Politicians including Prime Minister Rutte repeatedly said the problems would be dealt with speedily and resolved generously.[2] The inquiry concludes "The empty promises are a disappointment again and again". Key decisions revolved around money, not safety or care for residents: "for a long time one element was missing from the debate on the many reports and recommendations: the moral perspective".

The perceived unreliability of the Dutch state and the companies involved has had knock-on consequences for the "license to operate", the granting of concessions and regulation of other mining and energy projects. This hinders the transition to renewables such as windmills, solar energy and geothermal energy.

The economy and reputation have suffered. Widespread damage and a flagging reinforcement program have disrupted the housing market for a considerable time. Compensation for depreciation (€1.4 billion) will not compensate for the inability to sell homes when residents want to or need to. This situation has harmed residents' freedom of movement and damaged Groningen's reputation as a place to live. With respect to livability, however, the negative impact was small: in the eyes of residents the region continues to be a good place to live, also for its identity and cultural heritage (Hupkes et al. 2021).

The *health and well-being* of residents are affected by all the above factors together, combined with the seismicity itself. Residents feel powerless and unsafe.

[2] The Dutch expression they used is "ruimhartig", which literally means with a generous heart.

This in turn results in chronic stress. We quantified the consequences of the health impact, on the basis of a large representative national health survey (>16,000 respondents in Groningen), and concluded that authorities should expect at least 5 deaths per year as a result of these health complaints (Postmes et al. 2018a).

7.3 Reflection: Science, Power and Politics

What was the role of science in this case? The inquiry is scathing about the very close collaboration between exact science, government and operator in the assessment of risks.

This is an early forerunner of what is currently praised as the "triple helix", in which the government, business community and science work together to create innovations and new insights … The focus of the research questions remained on gas extraction for too long, instead of on the effects of gas extraction. The Committee finds that there was a blameworthy lack of ambition to increase the expertise (Parlementaire enquêtecommissie aardgaswinning Groningen 2023).

This "closed knowledge stronghold that is the mining sector" remained intact until the regulator broke ranks in 2012. The inquiry repeatedly describes how these parties conducted science and used the results as "objectionable" (pp. 42, 77 and 78). We see four problems:

In this partnership, to paraphrase Slovic, *scientific risk assessment was used as an instrument of power* (Slovic et al. 2004). When residents first noticed earthquakes, this was said to be impossible due to the geophysical makeup of the field. When earthquakes were proven, it was claimed they could not originate from the field. Then it was said earthquakes were so small, and they hardly caused damage. When the regulator falsified these claims and advised cutting production, new research was commissioned. This showed how much was unknown and how wide the margins of error were. Now, the *Gasgebouw* claimed that the regulator's advice was unsound: cutting production would reduce risk (Parlementaire enquêtecommissie aardgaswinning Groningen 2023). This is a deplorable abuse of science, first to construct certainty that production is safe and, when this is disproven, to construct uncertainty about mitigation.

Second, the scientists who developed the risk assessments were a relatively small group working for many different (often competing) institutions, all of whom were dependent on the operator for data and often funding. Together this "closed knowledge stronghold" disregarded insights from other disciplines, other approaches to risk assessment or alternative views about the hazards of cumulative damage (Parlementaire enquêtecommissie aardgaswinning Groningen 2023; Onderzoeksraad voor Veiligheid 2015). The scientific reputations inside this stronghold, meanwhile, meant that their own approach to risk assessments was presented as an exact science based on solid facts. In this way, *structural shortcomings of science in the sector made a balanced risk assessment impossible* (Wynne 2015).

Third, the inquiry concludes there was a "shortage of knowledge" and "instead … a lot of hollow reassuring words" (p. 77). One problem was an absence of good data. Seismometers were not sensitive enough at first. Ground motion detectors were installed quite late, and then, in 2018, it was discovered they were poorly calibrated: only 4 of the 114 were accurate. Most sensors underestimated ground motion by half (Staatstoezicht op de Mijnen 2021). Another problem was an over-reliance on assumptions instead of observations: policy researchers concluded that government decisions were based on "models [that] harbor too many uncertainties and are based on too many poorly founded assumptions" (p. 9) (Derksen and Gebben 2021). We conclude that the *science in the sector was not sufficiently reliable for good risk assessment*.

Finally, the inquiry has revealed how the *Gasgebouw* and the operator used scientific expertise to advance their interests. The civil servants in the *Gasgebouw* wrote in 2013 that "the ministry seeks to move the regulator in the direction of the vision of professor …" (p. 682) (Parlementaire enquêtecommissie aardgaswinning Groningen 2023). This person was then appointed to several influential committees. One advised in 2015 that risk regulation should be based on an exact scientific approach, even though the scientific knowledge at that time was quite imprecise. Another was formed when the regulator expressed criticism about the operator's plan to abandon the current mitigation strategy and adopt a new one, based on a newly developed hazard and risk assessment model. The regulator had warned that the model was non-transparent, unvalidated and potentially unreliable. Despite it being untested in practice, the professor contradicted this and told parliament it would be irrational not to use it: this was "the best that science has to offer". Most of the regulator's concerns were later borne out: despite its excellence there were so many unreliabilities that it soon became very contentious. We conclude that there was a *selective use of safety science for political purposes.*

7.4 Conclusions and Implications for Science and Safety

What can we learn from this case? First the role of risk assessment and risk management itself. To date it focuses only on the high risk: catastrophic earthquakes causing deaths. When extraction began (1960s), this was ignored. When earthquakes did occur, the risks were considered negligible (1990–2012). After 2012, when earthquakes had increased in number and magnitude, everyone agreed that risks were substantial after all, but the issue had become contentious, there were large uncertainties and many unknowns. Different risk assessments (based on inspected buildings vs. modeled impacts) produced contradictory results. Throughout this time, the risk assessment has ignored the impact of "smaller" hazards such as damage.

All risk assessments revolved around dollars and deaths: they assumed that a rational decision would put financial benefits against lives lost. Above we have provided several illustrations of the fact that these metrics ignore many costs. Even if no one dies, a situation might be undesirable, inhumane or unlawful. This approach

is also problematic because it turned risk management, mitigation and compensation into financial questions, rather than questions of effectiveness, achievability or morality.

We conclude that the incompleteness of risk assessment contributed to a slow-onset creeping disaster. Risk assessment was uncertain and contradictory and therefore a poor foundation for policies. Risk assessment ignored smaller risks and so failed to stem a growing hazard. And by ignoring the hazards of mitigation, a new problem could be created. Risk assessment may have been incomplete because its scope was decided inside the "closed stronghold" of the mining sector itself. And to us at least, it appears that risk assessment was used by the Gasgebouw to define risk and thereby block any dissenting views on it, to circumvent the regulator and influence parliament. Risk assessment was thus used to control revenue and costs and to exert power (Slovic 1999). This reminds us less of science than of "*scientism*" as an anti-democratic and "instrumental assessment and control of selectively defined risks" (p. 109) (Wynne 2015).

We can also learn from the public debate about risk in Groningen. The risk literature loves its dichotomies: risk assessment versus precaution (Lofstedt 2011), rational analysis versus affective responses (Slovic et al. 2004), expert judgment versus public perception (Gardner and Gould 1989) and quantitative versus qualitative risk assessment (Breakwell 2014). All these occasionally entered public discourse as frames to explain a complex issue. Implicitly or explicitly, such frames invite audiences (such as the wider Dutch public) to take sides. Are you with the people or with the experts? Should we take precautions now, based on gut feelings, or should we wait for a sober assessment of risks? As many have pointed out, these are false and divisive choices (Slovic et al. 2004; Slovic 1999; Breakwell 2014). It is evident that precautionary measures should have been taken much sooner (as the inquiry concludes) but that does not preclude good risk assessment: the challenge is to better integrate the two in policy decisions. Similarly, risk analysis becomes more rational when it integrates affect and emotions, experts and the public become wiser through collaboration, etc. We conclude that the classic dichotomies of the risk literature introduced noise.

A third reflection concerns civil society. How could this happen in a highly developed democracy? Key aspects of the partnership between government and industry were undisclosed. The oil companies wanted "to not make public the participation of the State in the extraction and sale of gas". Even parliament was not informed. One ministry (Economic Affairs) was tasked with three different and potentially conflicting public interests: the maximization of profit, energy supply and public safety. All this may explain why the *Gasgebouw* could resist mounting pressure after 2012. The regulator was worked around. Social movement organizations, journalists, politicians and mayors raised public awareness, and the seriousness of residents' problems was documented in research and opposition in parliament mounted. But the *Gasgebouw* only responded when the judiciary investigated the operator's liability for criminal prosecution. This "had enormous impact on the decision-making within the Gasgebouw" (Parlementaire enquêtecommissie aardgaswinning Groningen 2023). It is ironic that captains of industry do not change because of mounting evidence

that their operation is risky and causes harm, but because they themselves risk being prosecuted.

What does the case tell us about climate change? Gas extraction has similar risks to various "green" energy initiatives: storage of greenhouse gases, hydrogen or geothermal energy. Here, we also see that the interests of government and corporations are aligned. Our case shows there is a need for critical dialogue about these new technologies, close monitoring and transparent decision-making. One further lesson is that local residents may be the first to notice negative impacts: regulators and operators need to heed their perceptions and concerns.

We heard in Groningen an "extraordinary times call for extraordinary measures" argument that may become more common as the climate changes. Extracting more gas was justified by it being the "ideal transition fuel" to ward off climate catastrophe. This may have been a convenience argument. The inquiry shows there was only ever one goal: to maximize profit. But either way, ignoring risks backfired badly. The field rapidly became a loss-maker, and the events eroded the public license to operate also of "green" initiatives such as geothermal energy. We conclude: extraordinary measures call for solid risk governance.

Acknowledgements The authors are affiliated with the Knowledge Platform (Kennisplatform Leefbaar en Kansrijk Groningen), funded by the Netherlands Ministry of Economic Affairs and Climate and by local government in Groningen.

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