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Safety Management

Corinne Bieder · Gudela Grote ·
Johannes Weyer *Editors*

Climate Change and Safety in High-Risk Industries

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Safety Management

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Editors

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Series Editors' Foreword

This collective volume is the fruit of a workshop organized by NeTWork (New Technology and Work), an international, interdisciplinary group of academics, regulators and practitioners. NeTWork aims to provide concepts and methods for addressing individual, organizational and societal risks created by technological development, for evaluating the state of the art of technology management, regulation and risk control and debating the way forward. Since 1983, NeTWork has held annual workshops relating to the overall theme of new technologies and work. Workshops have covered a wide range of topics that included human error, accident investigation, training, distributed decision-making and management. Recent preoccupations have focused more specifically on a theme of great scientific and social significance: the safety of technology-intensive systems and the role of human contribution to either failure or resilience of high-hazard activities.

The Foundation for an Industrial Safety Culture (FonCSI), a public-interest research foundation that sponsors R&D activities on the organizational dimensions of industrial safety, is proud to support the activities of NeTWork since 2010.

The volume addresses the issue of climate change and its increasing impact on the safety of high-hazard activities. As often in NeTWork discussions, questions and challenges for safety managers and regulators are raised, but the workshop also raised more philosophical questions that challenge the scope of safety research and the role of safety scientists themselves. Many thanks to the godmothers and godfather who organized this workshop, Gudela Grote, Corinne Bieder and Johannes Weyer, and to all the contributors for their thought-provoking contributions.

December 2023

Eric Marsden
FonCSI
Toulouse, France

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Chapter 1
Introduction

Gudela Grote

Abstract This chapter outlines the aim of the book which is to explore the relationship between new challenges posed by climate change and the continued efforts to manage high-risk industrial installations well. A summary of the book chapters is provided to highlight theoretical, methodological and case study-based empirical insights into this complex relationship.

Keywords Climate change · Safety management · High-risk industries · Theory · Methods · Case studies

This book contains insights garnered from a workshop held in October 2022 at Royaumont Abbey near Paris, a place that by its own existence demonstrates how sustainable change in response to the manifold twists and turns in human history is possible. The aim of the workshop was to explore how climate change as one of today's grand challenges interacts with another longstanding challenge, that of benefiting from new technologies while keeping their risks at bay through risk and safety management. Climate change obviously is closely intertwined with the use of technologies as they have evolved over time, from burning coal to nuclear energy, from the first car engines to aviation. Climate change not only results from using these new technologies, but also induces new threats to using technology safely, as discussed under the rubric of Natech, referring to natural hazards' potential to cause industrial accidents (Krausmann et al. 2011). The reciprocal relationship between high-risk industries and climate change has been captured by the concept of double materiality (Adams et al. 2021; Gourdel et al. 2021). Aviation or oil and gas are two emblematic industrial domains whose very existence is challenged in a context of climate urgency (see the flight shaming movement for example), while nuclear power production is revitalized as a "green" technology (Tillement and Garcias 2021; Verma 2021).

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All actors, including high-risk industries, are urged to reduce their contribution to climate change, imposing new challenges to organizations in which safety has a certain importance and level of priority. In this push for transformation driven by the need for sustainability, what is at stake for safety (Blokland and Reniers 2020)? Some tentative connections have been discussed, for instance regarding food safety (Pires et al. 2020), workers' safety, especially in relation to heat stress (Dasgupta et al. 2021; Kjellstrom et al. 2016; Schulte and Chun 2009; Schulte et al. 2016), safety of infrastructures (Nasr et al. 2021) and public safety (Stroebe et al. 2021). Yet, it seems that only a small part of the interplay has been explored despite their coexistence at all levels (users, operators, organizations, industry, governance) in practice.

In a broader perspective, considering societal subsystems such as energy, transportation, agriculture, industry or health systems, sustainable transformation is a huge challenge that policymakers and civil society must address to prevent climate collapse. As some authors have already noted, more academic attention is needed regarding the safety implications of disruptive, sustainability-driven changes in socio-technical systems (Iakovleva et al. 2021; Kivimaa et al. 2021). In this context, safety issues can be considered as both side effects (e.g., the volatility of renewable energy sources or chemicals used for plant-based nutrition) and important facilitating conditions (e.g., users' safety expectations regarding existing technologies or strong actors/institutions that provide safety standards for new products and infrastructures). Consequently, transforming complex socio-technical systems requires not only the dismantlement of prevalent system structures and the achievement of a stable future state, but also managing the process of establishing new practices in a safe and reliable manner without interrupting important systemic functions and services.

In the chapters to follow, some of these challenges are addressed with a theoretical, methodological or case study-based empirical lens. The first two chapters by Jean-Christophe Le Coze and Julien Etienne discuss the relationship between climate change and safety management from a theoretical perspective. Le Coze argues that climate change should not be considered in isolation but in relation to other changes, especially globalization and digitalization of industrial workflows, as they conjointly affect and are affected by concerns related to the safety of high-risk industries. He proposes the concept of Post Normal Accident as an analytical lens to conceptualize interactions at different scales from local to global, stressing that tight coupling of systems and complex interactions between components of systems need to be considered not only within organizations, but across organizations and institutions as they act in increasingly dense and entangled networks. In a similar vein, Etienne asks whether and how industrial safety research will be able to inform the socio-technical adaptations needed to accommodate threats to safety stemming from extreme weather events and global warming. Critical infrastructures will have to be made "climate-proof", but this may entail fundamental trade-offs between technical, economic, political and social objectives. Adaptation limits have to be acknowledged and illusions of control dismantled in the hope of finding new tools to address the monumental challenges ahead.

Alena Bleicher and Johannes Weyer propose methodologies that can help to handle the complexities involved in understanding and shaping the interactions between industrial safety and climate change. Using the example of geothermal energy, Bleicher suggests that real-world experimentation may be a way forward to continuously gather, reflect and revise knowledge on the effects of technological, organizational, economic and political transformations in order to guide future action. Small-scale, controlled experimentation outside scientific laboratories can be understood both as an analytical lens and as a design principle. Central characteristics of such experimentation are derived. Weyer discusses agent-based modeling (ABM) as another methodological approach to comprehending the dynamics of complex socio-technical systems. ABM can serve to evaluate the effectiveness of different policy measures aimed at enhancing safety or promoting sustainability (or both). A simulation framework based on analytical sociology is presented which focuses on people's everyday practices, bounded-rational decision-making and governance concerns. Examples are provided for how ABM helps to understand individuals' reactions to policy interventions in the realms of personal mobility and energy supply.

In the final section of the book, three case studies are presented to illuminate the particulars in the relationship between climate change and industrial safety management. Ole Andreas Engen and Claudia Morsut address how public authorities understand climate risks and their consequences in the context of the petroleum industry in Norway. Their case study focuses on Stavanger as it is experiencing socio-economic transformations of its main industry, consisting of the redesigning of prevalent system structures and the rebranding of the Municipality from oil to energy capital. This approach is sustained by the introduction of new practices, complying with climate change considerations, without interrupting important systemic functions and services. Tom Postmes, Nienke Busscher, Sanne Hupkes, Agustín De Julio and Ena Vojvodic present a case study of the Groningen gas field. They investigate the role of science and knowledge in the assessment, monitoring and management of escalating earthquake risks associated with gas extraction. The lessons from this case are relevant for renewable energy initiatives such as hydrogen storage and geothermal energy. Gas extraction itself will also continue, despite the International Energy Agency's conclusion that no new fields should be developed to reach net-zero emissions by 2050. Natural gas may be the best of the worst during the energy transition: gas-fueled power plants have lower emissions and combine well with renewables. Lastly, Stéphanie Tillement discusses French nuclear infrastructure as another case for how economics, politics and technical and environmental contingencies interact and affect safety and climate goals. Climate goals as well as energy security have motivated the urgent call for increased nuclear production capacity in France. Meanwhile, recent incidents have highlighted (unsuspected) fragilities in existing facilities, and development efforts for new facilities have been largely unsuccessful. Ways out of the current dilemma focused on accommodating short-term stability needs and long-term development of the industry are discussed.

In the concluding chapter, some broader insights are discussed and steps proposed to more fully consider the interplay of climate change and safety management in research, industrial practice and policymaking.

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Chapter 2
Climate Change, Global Scales and Safety

(Post Normal Accident)

Jean-Christophe Le Coze

Abstract The argument of this chapter is that climate change is one change among many which currently affect the operating landscape of safety-critical systems, and that safety research should adapt its lenses to capture these changes. Climate change, which could, perhaps, preferably be described as global warming, should therefore not be considered in isolation but in relation to other changes (e.g., globalization, digitalization). One task for safety research is therefore to identify, to empirically study and to explore the implications of such changes for safety but also to address their theoretical consequences. Following a short presentation of a case study in the chemical industry, the proposition of Post Normal Accident is briefly introduced. It provides analytical lenses to conceptualize change through the notion of global scales shaping new causal regimes in safety, causal regimes expanding coupling and complexity well beyond Perrow's initial use of the notions in the 1980s.

Keywords Global warming · Safety-critical systems · Globalization · Coupling/ complexity · Post Normal Accident

2.1 Introduction

The argument of this chapter is that climate change is one change among many which affect the operating landscape of safety-critical systems. Climate change, which could, perhaps, preferably be described as global warming, should therefore not be considered in isolation but in relation to other changes (e.g., globalization, digitalization). One task for safety research is to identify, to empirically study and to explore the implications of such changes. Following a short presentation of a case study, the proposition of Post Normal Accident (Post NA, Le Coze 2021a, 2022,

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2023a, b) is briefly introduced. It provides analytical lenses to conceptualize change through the notion of global scales shaping a new causal regime in safety.

2.2 An Empirical Illustration

In a case study of a chemical plant of a small US multinational in France (> 3000 employees worldwide), it appeared that within a decade, from the late 1990s to the early 2010s, this site of the company went through an important number of changes which substantially modified its mode of operating (Le Coze 2021b; Le Coze and Dupré 2022). These transformations amplified the digital, network and global properties of the plant. Automating (more sensors on chemical reactors connected to computers to supervise reactions), computerizing production (more information systems through workflow to manage logistics and maintenance), externalizing several of its activities (waste treatment plant, maintenance, boiler) and restructuring its organizational design toward a higher level of centralization and standardization (through a matrix structure) by the multinational's head office in order to improve worldwide cooperation and control, the plant illustrates indeed this change of mode of operating, its level of interconnectedness across frontiers, organizations and distances that many safety-critical systems have experienced, including in the chemical industry (Avenas 2015).

Within a decade, the plant moved from a more autonomous, a more geographically "isolated" and a more "independent" mode of operating to a very different configuration which modified but also increased its level of interconnectedness. Automating and computerizing its processes created new ways, in real time and far more intrusively, of interacting with corporate actors of the multinational in the USA. These actors could indeed be in touch with daily practices of the plants thanks to the potentialities offered by its information infrastructure in ways which were simply impossible before. Externalizing activities increased the number of people to interact with because it multiplied the number of interfaces outside the company through multiple subcontracted organizations.

Modifying the organization through a matrix structure also meant far more links with headquarters, corporate and sites across the world to share information, to meet other employees during trips abroad (e.g., to India, to USA) and to implement standards audited by experts inside and outside the company, experts from sites who travel around the world to perform these audits. Within ten years, there was a profound modification of scale within which the plant operated and of work experience for employees. It was far more networked, digital and global. These had concrete implications for employees' practices, social interactions and identities, from operators to site managers. Of course, the effects of such processes were not of the same kind depending on employees' hierarchical levels and tasks (Le Coze and Dupré 2022). This description in the chemical industry is found in other safety-critical contexts which have been following similar paths (Dupré and Le Coze 2021).

An example is provided by Kongsvik et al., in the maritime industry, “while ships were traditionally autonomous organisational systems that the seafarers on board could – and were expected to – master alone, ships are now increasingly part of large networks of ships, internal and external IT systems, shipping companies, yards, certification agencies and national and international regulations” (Kongsvik et al. 2020) … in other words chemical plants (and ships) are connected to broader chains of causation allowed by global processes in different ways than in the past.

This is a materialization of the increased flow of people, data, goods or capital through expanding multinationals and tighter control of operations exerted across national borders (through standardization, computerization/digitalization) while also expanding their networks’ configuration into global value chains (externalization) (Baldwin 2016). This is a social, economic, political and cultural phenomenon with great consequences (Martell 2017). Their mode of operating is associated with a range of actors, organizations and institutions which are remote to their geographies or nationalities. They are connected to a global scale (Fig. 2.1).

Interestingly, there was another dimension linked to these changes of the plant, another change which situates it at another scale too, at a “second level” or referring to another “dimension” of global scales, yet of a different kind. During the study, two indications of this other change of scale were identified. The first was when operators mentioned how cold or hot it was at times in the building where they worked. This building was the main production one, with all the chemical reactors.

It was largely open to the outside through very large gates whose doors remained open most of the time for forklift trucks to circulate. It was an uninsulated warehouse

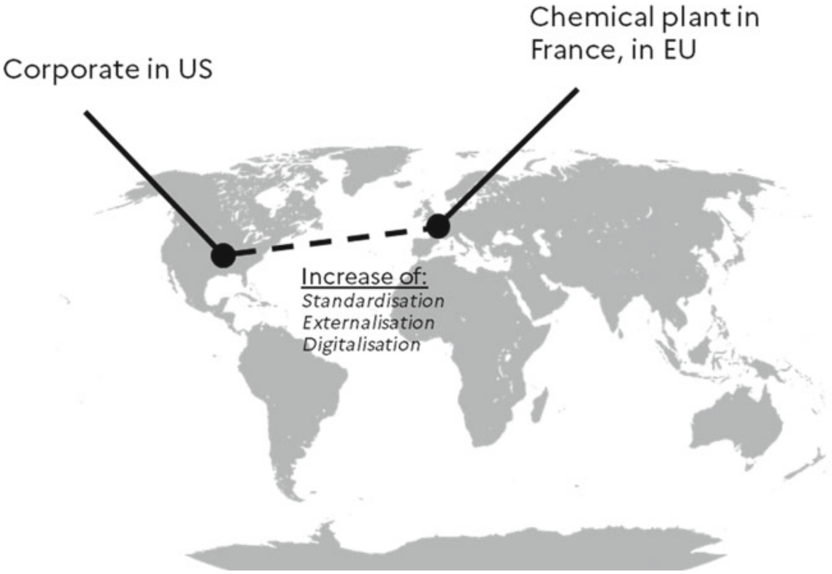

Fig. 2.1 More globalized plant. *Source* Author’s own work

made of metal, filled with chemical installations (pipes, reactors, valves). Their response was to organize work to cope with these extreme temperatures, wearing warm clothes in winter, drinking a lot in summer (but without the possibility of taking off their protective equipment) and staying inside the air-conditioned control room when possible.

However, this option was not possible for all the workers, because some activities had to be performed outside of the control room. These periods were not long (a few days over a year) but sufficient for the operators of the plant to mention them during the study. The second indication was the issue of accessing water to cool down chemical reactions during production stages, but also in case of a loss of control of an exothermic reaction. It is one of the safety barriers in the defense in depth of the system.

Because the plant was pumping water out of a well shared with a nearby town, they had designed sensors to monitor groundwater levels. These sensors were reported on computers' interfaces which allowed them to make sure that they always had enough water in the system. In case of a low level in groundwater, alarms would be triggered, and they had, potentially, to reorganize production. However, this situation was never experienced, and sensors were almost forgotten by operators.

These two examples illustrate another change of scale, this time at the planetary level, not only as a connection to the trends of economic, social and cultural globalization discussed above but as a connection with the natural environment, which leads to another dimension of global scale. Environmental change at the planetary level through human activity is described as the phenomenon of anthropocene (McNeill and Engelke 2015). As much as economic, technological and cultural globalization modified the plants' configurations and operating mode toward a global scale, the anthropocene was currently modifying the risk profile of safety-critical systems.

Today, a decade after this study performed in 2011/2012, heatwaves are more likely to occur, drought might result, and catastrophic natural events (e.g., floods, storms, megafires) might increase in intensity. What the plant experienced during the study was only a glimpse of what is potentially coming. Indeed, Europe, the location of the plant described in this paper, is particularly exposed to extreme events (e.g., France, Germany), although not as much as other countries (e.g., Haiti, Pakistan, Bangladesh and Thailand), yet, more than many others (e.g., USA, Brazil) (Germanwatch 2021).

As an illustration, the 2022 summer was particularly alarming, with many fires across France, in places without histories of such events (e.g., fire pits in Southwest—Gironde, and West—Brittany, of France), a topic which is part of the consequences of the global warming scenario (Zask 2019). Beyond France, the heatwaves also correspond to very unusual temperatures for European geography which also suffered several fires (e.g., Germany, Italy, Spain and Portugal), low level of rivers (e.g., the Thames, the Loire, the Gironde and the Rhine) and of hydraulic reservoirs (Norway's reduction of electricity production); storms (a particularly devastating one in Corsica in August 2022); glaciers melting then collapsing (in Italy for instance in July 2022); and a marine heatwave (linked to Corsica's storm in August).

2.3 From Natech to Socio-Natech

Events (e.g., droughts, storms, floods, megafires, but also snow) which can trigger accidental scenarios in safety-critical systems (e.g., refineries, chemical plants, nuclear power plants) have been conceptualized as Natech (natural events triggering technological accidents). Risk assessments take them into account to anticipate potential effects on critical infrastructures and safety-critical systems (Mikellidou et al. 2018). From a socio-technical point of view, global warming is therefore a new condition, bringing new threats to safety-critical systems. Coping with heatwaves in terms of operational practices or dealing with a lack of water to cool down reactors is significant modifications.[1] The same can be said concerning the exposition to floods (or megafires). These new potentialities have concrete operational, managerial and regulatory translations:

- Modifying working hours to accommodate temperatures (i.e., starting earlier in the morning when temperatures are lower) is one option—beyond insulation or air conditioning—which can require new legal and human resources arrangements and negotiations. It might also create new issues for organizing production across departments, services, organizations (e.g., subcontracting) or sectors in safety-critical systems, with cases for which such arrangements are difficult to implement in practice.
- Designing and authorizing an alternative mode of operating (for which one important barrier in the defense-in-depth protecting from the risk of runaway reactions—the cooling down systems based on water—might be inoperative during some periods in the year) is a challenge involving the collaboration of engineers, managers and regulators. Additionally, low level of river might also limit negotiated threshold of flows of pollutants for chemical plants, and heatwaves could alter water treatment processes, as much as electronic components of systems.
- Preparing for extreme events such as flooding requires a thorough establishment of contingency planning based on risk assessments which incorporate the consequences of rising levels of water, with a certain speed and intensity in sometimes complex processes, as shown in the USA with the Arkema chemical plant during the Hurricane Harvey in 2017 (while the same applies to an exposition to megafires).

In other words, Natech is also very much a Socio-Natech problem. Indeed, how will these prevention and mitigation strategies (e.g., modifying working hours, designing and authorizing an alternative mode of operating, preparing for extreme events) be implemented in digitalized, externalized and networked safety-critical systems? What to make of all these global scale transformations and their effects on the reliability, safety and performance of safety-critical systems which has been a topic for several decades? How to conceptualize these large-scale evolutions, from

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[1] Several nuclear power plants in France in 2022 were shut down because of the low level of rivers, impairing cooling systems, contributing, in the context of Ukraine's war, to a rise of energy costs.

increase of flows through globalized processes to climate change and their likely influence of operations?

Overall, these are indeed radical transformations of safety-critical systems contexts which have occurred within a few decades. Our argument is that these global scales are a level of change which is worth reflecting upon in the safety field. In this respect, a combined conceptual and empirical proposition to do so, to tackle this "*challenge of change*" (Hale and Baram 1998) is Post Normal Accident (Post NA, Le Coze 2021a, 2022, 2023a, b), to which we briefly turn.

2.4 Post Normal Accident (Post NA): Global Scales (New Causal Regime)

The Post NA proposition comes back on the seminal book, Normal Accidents (Perrow 1984), to provide an update for our contemporary era. There is no need to introduce in detail Normal Accidents (NA) (Perrow 1984). As most readers know, NA's contention is that coupling and complexity of high-risk systems create opportunities for catastrophes, and some exhibit such features (e.g., nuclear power plants). The book has an iconic status, within and beyond academia (Clearfield and Tilcsik 2018). One reason is that the book helped us reason about the new level of complexity induced by the advent of large technical systems in the 1960s and 1970s (e.g., aviation, oil and gas, nuclear industry, nuclear weapons, dams).

The picture is now of course quite different from the 1980s. Beyond the flows triggered by globalization, the ecological crisis including global warming affects high-risk systems through an increase of natural catastrophes (e.g., storms, floods, droughts, heatwaves, megafires) which threaten their mode of operating. The notion of Natech (or, as suggested in this paper, Socio-Natech) has conceptualized these relationships between nature, socio-technical systems and safety, one important example for safety being the tsunami flooding the Fukushima Daïchi nuclear power plant in 2011, in Japan (Pritchard 2012). In this respect, socio-technical systems have become (global) eco–socio-technical systems.

These global trends create a very different situation for socio-technical systems in comparison to the 1980s, and two categories have been proposed in the past twenty years to update our perspectives on risks in the twenty-first century: systemic and existential risks. Systemic risks are these threats associated with the increase of flows that globalization entails (Goldin and Mariathasan 2015; Goldin 2020). A problem somewhere in the world can affect remote or distant places through the diversity of flows shaping globalization, through rippling effects.

Existential risks are these threats with the potential to affect societies' survival and perhaps even that of humanity (Ord 2020). By the scale of their potentialities, they also address, like systemic risks, a global level of analysis. One existential risk is the prospect of a drastic degradation of living conditions due to the anthropocene, in a more or less distant future, depending on geographies, and societies' actions in the decades to come (Gemene and Rankovic 2019).

Existential risks such as the anthropocene combine a number of highly interdependent dimensions, themes and measured variables at the global scale associated with diverse types of impacts including global warming (i.e., carbon dioxide emission, rising water levels, ice melting, average temperature increase, acidification of oceans, health-related effects), biodiversity loss (i.e., eutrophication of oceans, forests devastation, invasive species, agriculture extension and fishing—ocean depletion) and pollution (i.e., plastics, wastes, pesticides, endocrine disruptors). Much as for the category of systemic risks, the relationships are complex, in which complex circular causalities dominate.

Furthermore, many safety-critical systems which were core to Perrow's argument (e.g., aviation, nuclear, oil and gas industry, maritime transport, chemical industry) are now at the heart of globalization and the anthropocene (large technical systems constitute the infrastructures of globalized flows and of nature's degradation, Le Coze 2023a, b). Consequently, Post NA argues that these contemporary unfolding realities constitute a new causal regime at the global scale for safety. There is a level of connection between many safety-critical systems and their environments which has moved safety research to another level of causation and understanding (a change of our cosmology in the anthropological sense, see Latour 2015), which is also a change of our understanding of their scope, scale and time frame …

2.5 Conclusion

Over the past three decades, the operating landscape of safety-critical systems has profoundly evolved, and the argument of this chapter is that climate change should be linked to these profound changes of the past decades. This reformulates our understanding of the conditions of reliability, performance and safety of such systems. They are indeed connected to broader chains of causation, regime of causality, created by global processes which differ from the past. Post Normal Accident (Post NA) is one proposition to conceptualize this new situation, describing a new causal regime, combining systemic and existential risks into a perspective of the contemporary situation of safety-critical systems and expanding coupling and complexity at the global scale.

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Chapter 3
On the Future of Industrial Safety Research

Julien Etienne

Abstract In this chapter, I ask what climate change does to industrial safety and what that means for the future of industrial safety research. Climate change already leads to and will cause more Natech events, that much is clear. Whether industry can adapt to prevent those is not. Engineering voices have recently stated that a handful of industries will need to be upgraded to withstand extremes, because they cannot be stopped at will and because they are critical. By contrast, the economical and rational response elsewhere will be to shut down when environmental conditions are too difficult (e.g., during a heatwave) and restart after. When and why make those trade-offs are key questions for industrial safety researchers. Besides, how far critical infrastructures can be "climate-proofed" largely depends on adaptation limits: the point at which it is neither physically nor socially feasible to adapt anymore. As adaptation becomes a key issue for industrial safety, so do adaptation limits. The challenge of thinking about industrial safety and climate change grows further when one considers that much of what is ahead is unknown. The weather extremes we are experiencing are only an appetizer on the menu we have cooked for ourselves. That challenges industrial safety research to the core. It shatters our illusions of control. It undermines our understanding of safety as an outcome of human–technology interactions. To wake up to that reality means shedding old ideas and embracing others. That is uncomfortable. It exposes researchers to controversy and practitioners to challenge. No one said it was going to be easy.

Keywords Extreme weather · Natech · Shutdowns · Adaptation limits · Control

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3.1 What Does Climate Change Mean for Industrial Safety and Safety Research?

It would be naïve to assume that all who ask this question share the same understanding of what climate change is and entails. Some see climate change as an agenda, such as sustainability or net zero, before seeing it as a set of physical facts. They tend to understand it through the demands emerging from government, business, NGOs or consumers. When the physical reality of climate change is acknowledged and physical facts are at the forefront, its likely implications, all the way to the "climate endgame" of global catastrophe (Kemp et al. 2022), are too often ignored, despite being hammered out time and again by the United Nations, the IPCC and prominent scientists. In fact, the latter's messages on the speed at which warming happens and the urgency of response are taken up at the margins of society only, but rarely at the center. That is true of academia too, outside climate and, more generally, Earth system sciences. There are politics at play, even a cultural war, as is most obvious in the USA. Those who speak of the worst impacts are often belittled or ostracized as radicals, ideologues or militants. Most persuasively, Bruno Latour has argued that climate change is at the heart of the political divisions that characterize the New Climatic Regime (Latour 2018).

Therefore, to address the question at the heart of this volume is to expose oneself to controversy. I will come back to that. But first, we need to think clearly, and for that, one needs to push aside emotions, interests (professional or otherwise), politics and the fear of social judgment and stay alert to the scourge of "the failure of imagination" that too many post-accident studies have noted.

3.2 What Climate Change Does to Industrial Safety

As I strive to follow these precepts, it seems to me that the core insights of climate science that matter most for our discussion are the following.

First, climate change—and other breaches of planetary boundaries (water cycle, nitrogen and phosphorus cycles, biodiversity, etc.)—is driven by the exponential growth of human activity. Many scientists argue, relying on empirical trends for support, that a "Great Acceleration" began in the 1950s (Lenton 2016; Steffen et al. 2015) and continues to this day, leading to ever greater impacts on the Earth system: greenhouse gas emissions, habitat destruction, soil erosion and biodiversity loss.

Second, climate change is a process unfolding at planetary scale: a complex, nearly closed system with profound inertia (e.g., Abraham et al. 2022). This means that, even if the emissions driving global warming were to stop altogether, the excess energy accumulated in the system to date remains there and the feedback processes it contributes to will continue to transform environmental conditions for centuries. This is what the IPCC calls "committed" climate change.

Third, key Earth system components that limit warming, either because they reflect solar energy back to space (ice caps) or absorb and/or store CO_2 (forests, permafrost), are failing rapidly because of the warming that has already happened. Some have likely passed critical thresholds already (McKay et al. 2022; Kim et al. 2023). As the Earth system passes these "tipping points", major drivers of further warming emerge: positive feedback loops integral to the Earth system that humanity has no tested ability to influence.

These insights are crucial for making sense of current and future extreme weather trends. I am referring to how temperatures, wind, moisture, storms, droughts and other phenomena fluctuate much more frequently away from the mean, as a result of global warming (Rodell and Li 2023). Extreme weather also means aberrant events, outside the range of known human experience: tropical storms hitting Ireland (Ophelia, in 2017), a temperature high of 49.5 °C in British Columbia, Canada (Lytton, in 2021), the flooding of one third of Pakistan (in 2022), to name only a few. The three insights mentioned earlier imply that this trend will continue and worsen for decades to come and likely not in a linear fashion. The actual path is unknown, but we can be sure of ever greater fluctuations as time goes on.

3.2.1 How Can Safety Be Managed Given the Path of Ever Greater Fluctuations Anticipated by Climate Scientists, and Can It Be Managed at All?

It is worth dwelling first on the safety challenges *we can foresee*. Global warming makes multiple technological accident scenarios increasingly likely. Droughts pose significant challenges for industrial processes that need cooling. They reduce water supply in case of fire. Heatwaves raise cooling needs beyond design expectations. They affect workers' capacity to carry out their tasks, to respond to unexpected events and therefore make human error more likely. Heatwaves may make stored substances that react exothermically more dangerous. Buckling rails and roads and melting tar may interrupt supply of raw materials but also make it more difficult or impossible for emergency services to reach a site in case of an accident. It could affect the structural integrity of site platforms. Droughts and heatwaves create conditions for wildfires that may reach industrial sites. Excessive air temperature makes it difficult and, beyond a certain point, impossible, for planes or helicopters to take off and fly at low altitude, also undermining emergency response capacity. Flooding and submersion may close off emergency routes, precipitate uncontrolled shutdown of hazardous processes, threaten the continuous cooling of certain stored materials (peroxides) by shutting down generators and lead to contamination of the wider environment if containment of hazardous substances is breached. High winds and storms can shut down power lines and damage buildings.

Ever more frequent and severe extreme weather events are projected to lead to increasingly frequent "Natech" events: technological accidents triggered by natural disasters (Mesa-Gomez et al. 2020; Piatyszek et al. 2017; Pilone et al. 2021). This is all the more likely as natural disasters are not only more frequent,[1] but several of them may hit a given area in close succession (e.g., drought, heatwave, wildfires, then flooding and landslide; De Ruiter et al. 2020). The climbing trend in Natech events is already perceptible in accident databases (e.g., Baraer 2021).

3.3 To Avoid Natechs, Should Hazardous Industries Shut Down or Upgrade?

In the UK, engineers, the chemical industry and industrial safety regulators have discussed these challenges in several recent publications (IMechE 2023; Environment Agency 2023; CIA 2021), offering tools and setting out recommendations. All state the urgent need for adaptation across hazardous industries.

The IMechE report focuses on cooling needs and how those could be addressed across sectors during heatwaves. It points out that the economics of adaptation will make it impossible to upgrade installations across all sectors. Indeed, it would be extremely onerous to install/upgrade and operate cooling systems across all the sectors that require them, so that they may withstand temperature highs of 50 °C or more. The authors expect instead that, in those sectors where shutdown is a relatively safe option, activity would stop for as long as very high temperatures last. The argument could be extended to other hazards associated with extreme weather. For example, it would not be possible for emergency services to tend to all industries and residential areas threatened by a major wildfire. There too, shutdown would be the economical response.

There are further dimensions to the unaffordability of adaptation. Ever more frequent and extended shutdowns will likely dampen the revenues of the businesses affected. That will, in turn, make the latter less financially capable of investing in adaptation as time goes by. The carbon neutrality agenda will add further pressure too: “some plants will have to close” (Pisani-Ferry 2021: 2).

Conversely, shutdown is both hugely onerous and hazardous in some sectors. Oil refining, gas processing and bulk chemical manufacturing are all process activities that operate continuously. The IMechE report sets them apart. Shutdown and restart at such facilities are complex, planned and can be highly hazardous: many process safety accidents at oil and gas, and chemical manufacturing facilities have happened during shutdown and restart (CSB 2021). Besides, they are also costly not only to the companies operating the sites but to the many third parties impacted. The IMechE report states that shutdown would not be the answer to extreme heat there. Instead, these facilities will need to adapt because “it is vital that their integrity and productivity is maintained in a future environment characterised by an overall increase in ambient temperatures and intense heat events” (IMechE 2023: 3).

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[1] www.visionofhumanity.org/global-number-of-natural-disasters-increases-ten-times; accessed on 20 May 2023.

IMechE's report thus sets out a trade-off: some industries will shut down when it is too hot, while everything needs to be done to keep the others running. IMechE's report references the issue of criticality, though only briefly. And yet, it makes the point clearly: it will not be feasible to adapt all industries so that they may operate safely during heatwaves. This raises the key question of *who defines what is critical to keep operating safely while environmental conditions deteriorate, and why?* This, I argue, is an urgent question that safety researchers could help address.

3.4 Physical and Social Limits to Adaptation

IMechE's call for cooling upgrades at some industries raises the engineering and commercial challenge of upgrading or redesigning some facilities for extreme, never yet experienced conditions. This leads to the question of **adaptation limits**, a concept absent from the EA, CIA and IMechE's discussion, but increasingly present in the climate science literature (IPCC 2023). There are *physical* (e.g., temperature highs, sea levels) and *social* adaptation limits: points where risks become intolerable (Martin et al. 2022). These boundaries might seem far away. And yet, some of them, the IPCC reported in 2023, have already been reached (IPCC 2023).

There is the matter of **physical** limits: the IMechE report hints at engineers' goal of upgrading commercial installations so that they may withstand weather extremes beyond any design parameters in existence. How one feels about that challenge depends largely on one's core beliefs in human ingenuity, technological progress, engineering prowess and innovation. It is, however, also a matter of time. For how long can engineers push installations to withstand ever more chaotic and extreme conditions? Many, like Vaclav Slim, doubt that it would be possible to transform industry (and that implies both mitigation and adaptation) in the very short amount of time this transformation must happen.[2] In other words, it may be that social limits will be met *before* physical limits.

Social limits to adaptation are not only economic, but the economic limits alone are daunting. Upgrading equipment and shouldering the considerable energy consumption required to maintain operations during ever more intense heatwaves are already unaffordable to many. As conditions worsen, it will become unaffordable to more and more players. Climate-driven shutdowns will reduce revenue and increase costs, depleting returns. Stress on installations from extreme weather will lead to higher maintenance costs. Cost pass-through to customers will drive economic activity down.

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[2] www.latimes.com/business/story/2022-09-05/the-energy-historian-who-says-rapid-decarbonization-is-a-fantasy; accessed on 20 May 2023.

As global warming progresses, more natural disasters will also hit installations, destroying some of them partially or entirely.[3] The mounting costs of natural disasters are well documented already (United Nations Office for Disaster Risk Reduction 2022). As they climb further, they will make insuring businesses against safety risks increasingly unprofitable, leading to insurer exit. This is seen already with homeowner insurance: "When risks increase, we should expect that insurers will retreat much faster than homeowners, as is happening now in California".[4] While there have been calls for public–private partnership[5] to insure against climate change, state-backed insurance schemes in the USA have progressively been replacing private insurance schemes, taking on the liabilities private insurers now consider too big for them. Such liabilities add to the costs of climate disasters these states are bearing and will impact the credit worthiness of public entities in the eyes of lenders.

Already, least-developed countries cannot keep up[6] with the damage caused by extreme weather. Poor areas in wealthy countries hit by consecutive disasters (such as Kentucky in the USA) are running out of capacity to rebuild,[7] while some US cities are being bankrupted by climate disasters.[8] Wealthier regions will reach their limits too as the impacts and the costs of disasters increase.[9] Several economists have warned that the crippling costs of climate disasters could trigger sovereign debt crises (Dibley et al. 2021; Zenios 2022).

The limits to adaptation are therefore also limits to the many layers of infrastructures and resources that have historically cushioned hazardous industries against the consequences of disaster: capital, insurance and the state. As global warming progresses, such limits are being pushed forward, not back.

3.5 Interim Conclusion

The discussion so far has meant to reframe the industrial safety goal in the rapidly deteriorating environmental conditions of a changing climate:

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[3] For example, wildfires have hit fossil fuel operations in Alberta in the Spring of 2023. www.nytimes.com/2023/05/17/climate/canada-wildfires-fracking-oil-gas.html; accessed on 20 May 2023.

[4] Testimony of Benjamin J. Keys, Ph.D., Hearing on "Risky Business: How Climate Change is Changing Insurance Markets", United States Senate Committee on the Budget, March 22, 2023, page 5. Accessible at: www.budget.senate.gov/imo/media/doc/Dr.%20Benjamin%20J.%20Keys%20-%20Testimony%20-%20Senate%20Budget%20Committee.pdf.

[5] www.theinsurer.com/close-quarter/kunreuther-climate-change-uninsurable-if-left-to-the-private-sector-alone; accessed on 3 July 2023.

[6] www.bbc.co.uk/news/world-58080083; accessed 20 May 2023.

[7] www.nytimes.com/2022/07/30/us/kentucky-flooding-natural-disasters.html; accessed on 20 May 2023.

[8] www.nytimes.com/2021/09/02/climate/climate-towns-bankruptcy.html; accessed on 20 May 2023.

[9] www.forbes.com/sites/chloedemrovsky/2022/07/13/the-cost-of-disasters-is-increasing-in-2022/; accessed on 20 May 2023.

- Climate change means more frequent and intense extreme weather, increasing the likelihood of Natech events all around the globe.
- Continuous, safe operations in an increasingly chaotic and extreme environment require that installations be modified to withstand such conditions. Adaptation will be expensive to develop, install and operate, in a manner many businesses will find unbearable.
- Where adapting installations will not be feasible, temporary shutdown is the most likely response to the safety risks posed by extreme weather. Intermittent operations, with more frequent shutdowns and start-ups, will likely become the norm across many sectors.
- Since adaptation to enable continuous, safe operations will not be feasible across all industries, trade-offs need to be made, and “critical” industries defined.
- Social limits to adaptation could be reached before physical limits, as climate change undermines the institutions and depletes the resources (capital, insurance, state support) that have historically helped cushion industry against the consequences of disasters.

3.6 Away with the Illusion of Control (Again)

These insights, which can inspire the research agenda of safety scholars, speak to what we can foresee. Yet, there is considerable uncertainty on what ongoing changes to the Earth system—which have no known precedent—will lead to; for example, the ongoing slowing down of deep-sea circulation currents caused by the melting of freshwater ice caps on the poles could lead to *other* dramatic changes to weather patterns (Li et al. 2023). There is much about the fluctuations we will experience soon that we do not know about. That, and the horizon of unstoppable warming climate science has drawn, has further, even more fundamental implications for safety research and how we answer the question: *how can safety be managed given the path of ever greater fluctuations anticipated by climate scientists, and can it be managed at all?*

Philosopher Pierre Caye (2008) has argued that our ever more chaotic world renders our morality obsolete, because that is a morality of mastery and control: either our own mastery or control or that exercised by others whom we depend on and trust (engineers, risk managers, regulators). That morality crumbles when we cannot take the stability of the world for granted anymore. Its claim to making sense of our place in the world weakens when our ability to effectuate our intent diminishes; when our aims to build and repair are denied by the elements relentlessly; and when the space in which we effectively have control shrinks as climate change presses us ever more closely against the wall of adaptation limits.[10]

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[10] Caye writes (my translation): “Initially powerless in the face of nature, man is arriving now to experiencing his own powerlessness towards his own actions, as if his quest for mastery and domination was eternally doomed to fail” (2008: 20).

Safety research uses concepts that speak to ideals of control: “safety performance”, “high reliability”, “safety management systems”, “layers of defense” and “human error”. It is not that safety scholars believe in absolute safety: from normal accidents (Perrow 1984) and the limits of safety (Sagan 1993) to epistemic accidents (Downer 2019), we know that “accidents happen”. And yet, safety research (or safety science) has been about understanding what makes man-made systems safe and identifying ways they can be made safer. If we cannot anchor our understanding of safety in the idea of control, then we need a new morality, one for a fluctuating, unstable world. More than ever, “to manage is not to control” (Landau and Stout 1979). And that morality needs a new perspective on the world, for we are not prepared for it. To quote Karl Weick, we need to “drop our tools”, stop “hold[ing] onto concepts, checklists, and assumptions that (…) weigh [us] down, reduce [our] agility, and blind [us] to what is happening right here and now and how [we] can cope with it” (Weick 2007: 6).

The authors of the IMechE report recognize this, to an extent, when advocating for momentous change to teaching at engineering schools and departments. They write: “current technical training and education provision for engineers was designed on the assumption of a climate-stable future” (IMechE 2023: 58). That future being forfeit, training and education for engineers need to be redesigned, this time for a rapidly warming climate. Mechanical engineers are not the only ones asking themselves fundamental questions about the way they think, research and teach. In a rich introspective piece and a completely different field, the International Law Association (2023) has also asked itself, among other things, whether it should embrace an Earth system’s perspective: a striking departure from a purely legal perspective on the world.

3.7 Letting Go of False Ontologies

Safety research is about a man-made world in which technology and humans interact against a passive décor. That “ontology” was wrong already 30 or 40 years ago, when leading contributions to the field were produced: the décor, then as now, was determined by complex processes, which sustained and regulated the conditions for human existence, and therefore industry too. We ignored and did not understand those processes. And yet, “like it or not, and whatever we may do to the total system, we shall continue to be drawn, albeit unawares, into the Gaian process of regulation” (Lovelock 2016: 120). An ontology that assumes the physical world is passive and malleable at will is obviously wrong today, because the décor is clearly no longer passive. It is no décor. As Latour, among others, has put it, it is an actor that re-acts to what we humans do, in ways that, so to speak, put us back in our place.[11]

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[11] “The Earth system reacts henceforth to your action in such a way that you no longer have a stable and indifferent framework in which to lodge your desires for modernization” (Latour 2018: 84).

Hence, there is a case for us in the safety research community—engineers, sociologists, ergonomists, political scientists, organization scientists and more—to embrace Earth system science (Lenton 2016) too. Earth system science challenges our ways of seeing and thinking the world. Bruno Latour, among others (e.g., Tsing, Haraway, Stengers, Morton), has written essential pages on what this entails, that I will not parrot here.

There is not only an intellectual case to embrace Earth system science. There is also a necessity, for, let us face it, we are not choosing to let climate change into our work and lives. Rather, climate change forces itself on us. Latour was keen to highlight that climate change is a power that the 175 states signatories of the 2015 Paris accord reckoned with, or else they would not have signed that treaty. The IMechE, CIA and EA reports all show how engineers, chemical industry businesses and regulators are facing to the facts, in their own way.

3.8 Preparing for Controversy

This leads me to a few final thoughts about the future of safety research. Researchers pride themselves on their distance from politics. Controversies abound in academia, but academic controversies are not the same as political controversies, and scholars have generally steered from the latter to avoid being considered militants. Yet, the idea that scholars, whichever discipline they affiliate themselves to, can avoid being drawn into political controversy on the matter of climate change is foolish. The considerable sums of private money that have been spent on discrediting climate science, by entities which had full knowledge of climate change based on their own, internal research, amply demonstrates this.[12] The politicized responses to the flurry of studies demonstrating ever more rigorously the role of various human activities in climate change and biodiversity loss further illustrate how inescapable the politicization of climate science is.

At a minimum, safety researchers working on climate change issues need to prepare for controversy, and that, inevitably, means reflecting on whether safety research contributes or not to perpetuating the root causes of climate change. Indeed, the core industries safety researchers have worked on are at the heart of the problem. Fossil fuel extraction and processing play an outsized role in driving climate change, ocean acidification and aerosols pollution. Fossil fuels and chemical processing drive the dramatic overshooting of the recently measured planetary boundary for novel entities (Persson et al. 2022). The chemical industry together with mining plays also a major role in the breakdown of biogeochemical flows (principally phosphorus and nitrogen). Transportation contributes greatly to aerosols pollution and, for air travel in particular, climate change.

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[12] Latour (2018).

From an Earth system's perspective, these industries are responsible for overshooting the planetary boundaries that define the safe conditions for human existence. This, in turn, transforms how we safety researchers have understood, after Rasmussen (1997), the boundaries of safe operations, and how we as a community define (and defend) safety.

3.9 If Research Shifts, Will Practice Too?

This chapter has dealt with the future of industrial safety research. But what about the future of industrial safety practice?

The implications of climate change for practitioners, in terms of risks and operational decisions, are here. In the Summer of 2023, the Hawaiian wildfires led utilities in several US states (including California) to announce they would henceforth shut down the electrical grid when conditions would be ripe for wildfires (as they were in Hawaii). Pre-emptive shutdown has arrived and will inevitably spread.

It is not unusual in industry to occasionally stop activity to manage the ebb and flow of demand. Shutting down some or all production activity for safety and maintenance reasons is also frequent, though this would generally be scheduled and managed to avoid or minimize interfering with commercial operations. Shutdown commanded by extreme weather events will interfere with demand and commercial operations, however. And that puts safety engineers in a peculiar position toward their production colleagues, leading to potentially tense and unpleasant conversations.[13] Learning to live with extreme weather within industry will therefore have to be a cross-company thing. It cannot be just the safety staff that educate themselves to the new world. Production staff too needs to be brought up to date. Emergency services may well prove an ally here: they too can clarify for all at an industrial site that, in an extreme weather situation, one that potentially triggers compounded disasters (e.g., an extreme heatwave causing wildfire, water scarcity and infrastructure failure), they would have their hands full and possibly tied.[14] Their ability to respond to an industrial accident would be limited.

I have argued that, in the face of climate change, industrial safety researchers will need to turn away from obsolete ideas about control and safety and embrace Earth system science. If researchers turn, will practitioners follow? This is very much for practitioners to decide: whether they choose to live in a fantasy world, one where safety is a product of humans interacting with man-made technology, or in the real world, where it is an outcome of man pushing and nature shoving back, harder.

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[13] It also puts industry as a whole in a peculiar situation toward investors and shareholders.

[14] Emergency services' capacity to intervene will be limited by the stress put by environmental conditions on infrastructures (e.g., buckling rails, melting tar), vehicles (helicopters less able to lift up and fly in hotter air conditions) and personnel.

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Chapter 4
The Experimental Perspective to Address Critical Infrastructure Security Issues in Times of Crisis

Alena Bleicher

Abstract This chapter suggests to make use of an experimental perspective for managing necessary transformations in high-risk industry. In order to do so, current trends in research on and with experiments beyond scientific laboratories are introduced and summarized and central characteristics of such experimentation are derived. Based on this, the potential of an experimental perspective is discussed from two angles: as analytical lens and as a design principle.

Keywords Collective experimentation · Experimental design · Non-knowledge · Learning

4.1 Introduction

Risk and safety issues in (high-risk) industries have to respond to a variety of (long-term) developments and changes, some of which are described as crises—e.g., the climate crisis. Related weather phenomena, such as droughts, heatwaves or floods, are expected to become relevant for maintaining critical infrastructures and related activities, ranging from ensuring healthy working conditions in hot periods to issues of safe operations in times of drought (Bieder and Villena-López 2022, see also Le Coze and Tillement in this volume). In addition, long-term trends such as digitalization or demographic changes are relevant, as well as the need for a fundamental reorientation of high-risk industries toward more sustainable operations. Regardless of whether they are framed as crises or as long-term developments, recent trends have in common that they generate new complexities and are associated with many uncertainties that must be taken into account when dealing with the safe operation of facilities and infrastructures. Against this background it is argued that empirically and conceptually new answers and approaches are needed in order to address new

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complexities and uncertainties as well as transformation processes that challenge risk and safety management (e.g., Bieder and Villena-López 2022).

In this chapter, I will follow up on this diagnosis and propose a perspective or approach that could be useful from both an analytical and a practical angle, allowing to address issues of (new) uncertainties, unavoidable surprises and non-knowledge: real-world experimentation. Such a perspective is not new in the field, as several authors have applied the experimental metaphor to explain processes and structures in high-risk industries (e.g., Felt 2017; Parotte 2020).

In the next session, I will clarify how the idea of (collective) experimentation is currently debated[1] and carve out main characteristics of concepts of experimentation. On this basis, I will then discuss the potential of an experimental perspective for the field of risk and safety studies from (a) an analytical point of view and (b) from a practical point of view.

4.2 Real-World Experiments, Real-World Laboratories, Collective Experimentation

Over the past decade, there has been a remarkable increase in interest in experimental concepts beyond scientific contexts (Weiland et al. 2017). Terms such as living laboratory, social innovation laboratories, transition experiments, urban living laboratories, real-world laboratories, home laboratories or collective experimentation have mushroomed in scientific and policy debates. What these terms have in common is an understanding of experimentation outside controlled spaces of scientific laboratories. This understanding dates back to the early 1920s, when the Chicago School of Sociology based on the work of John Dewey, Jane Adams and others invented the idea of social experimentation as a scientific research strategy aimed not only at knowledge production but also at the direct application of knowledge in order to improve living conditions in urban neighborhoods (Gross 2009). From these ideas evolved two strands of research that determine the current debate.

4.2.1 Collective Experimentation

The idea of *collective experimentation* has gained attention in the academic field of science and society studies and in the context of technological innovation in recent decades. The starting point is the observation that scientific practices of knowledge production and technology development are not confined to scientific laboratories, but "burden" society with the uncertainties inherent in knowledge production, in

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[1] My aim is not to provide a comprehensive overview of the concepts of experiments and experimental metaphors. For this, see among others Weiland et al. (2017) and van de Poel et al. (2017b).

particular with the effects of new technologies that can only be seen when the technologies are in use (Felt and Wynne 2007; van de Poel et al. 2017a). Due to unknown and partly irreversible effects on society, several authors characterized the innovation of technologies as well as the management of technologies as social experiments (van de Poel 2016). Already in 1994, Krohn and Weyer described a tendency to extend research processes and associated risks beyond scientific laboratories into the wider society (Krohn and Weyer 1994). While in those early days the debate was dominated by criticism of such a dissolution of boundaries, the focus shifted to understanding these experiments as opportunities for learning and demanding reflection on how they can be designed in a democratic way. In this sense, Latour (2011) emphasized the active role of society in scientific knowledge production and collective experimentation. Society and different groups of actors become active participants, for example, in the form of citizens' initiatives questioning wind turbines and other energy technologies, collecting data on environmental pollution or seeking research on rare and orphan diseases (e.g., Gramaglia and Babut 2014; Callon et al. 2009).

Authors who take up these ideas do not expect that it is possible to confine experiments and their outcomes to controlled spaces such as laboratories, whether in scientific buildings or defined urban areas, and clearly point to the limited possibilities of controlling the process (e.g., Gross 2010; van de Poel 2016). Society is inevitably exposed to foreseen and unforeseen developments, the positive and negative outcomes that scientific and technological developments have (Weiland et al. 2017; van de Poel et al. 2017a). Against this background, there is a call for greater public participation in technological innovation processes and thus a democratization of technology development. Thus, this strand of research focuses on exploring the relationship between science and society in the process of generating knowledge, which cannot be bounded temporally or spatially.

4.2.2 Urban Living Labs

Furthermore, there are practical, action- and solution-oriented transdisciplinary research approaches. These aim to provide answers to increasingly complex problems and related societal challenges, such as climate change, transitions in energy and transportation systems or demographic changes. They seek to accelerate transformations toward more sustainable societies (Schäpke et al. 2018). The *Urban Living Labs* Handbook refers to a crisis situation and understands urban living laboratories as test fields in which responses are generated to pressing challenges cities face, such as adapting the built environment to tackle extreme weather events like heatwaves or floods or decarbonizing transport through electronic vehicles and by reducing individual transport. These laboratories are intended as real-world contexts for designing, testing and learning from innovations in real time. Technical innovations are addressed as well as innovations in services, processes and new networks of actors (McCormick and Hartmann 2017; Marvin et al. 2018). Knowledge production and learning happen in intentionally created, spatially and temporally clearly defined spaces, and it is expected that results remain within defined boundaries unless they are intentionally transferred to other contexts. A strong emphasis is placed on the integration of diverse actors from science, policy and society; and societal actors are given an active role in these experimental settings as active co-creators of knowledge (McCormick and Hartmann 2017).

Experimentation beyond scientific contexts shares some understandings that can be considered key characteristics of experimentation beyond the laboratory:

- Experimentation in and with society is understood as a way or means of addressing complex socio-ecological and socio-technical challenges that are fraught with many uncertainties (non-knowledge is normalcy not an exception).
- The focus is on knowledge production, application, learning and revision. Failures are taken as opportunities for learning.
- Experimental settings are based on the acceptance that answers to certain questions may be surprising and unexpected, that answers are tentative, and that new knowledge may change the overall envisioned goal.
- Structures and processes in place make it possible to change strategies if necessary or to modify certain aspects.
- The integration of different perspectives and types of knowledge is central for experimentation beyond the scientific laboratory. And thus, the integration of societal actors is emphasized.

Experimental approaches are expected to provide better responses to the complexities and uncertainties of current developments and transformations than traditional approaches and thus to allow for better management of complex and uncertain situations. Experimental approaches are not reckless and do not ignore existing knowledge or established tools, but they put emphasis on what is not known and on dealing with unexpected developments (e.g., Gross and Hoffmann-Riem 2005; van de Poel et al. 2017a; Marvin et al. 2018; Bulkeley et al. 2016).

4.3 Experimentation as an Analytical Lens in Risk and Safety Studies

Current developments in the field of risk and safety (industry and infrastructure) are complex and fraught with many uncertainties. They require the transformation of practices and processes while keeping critical systems functioning and services operational and secure. The diagnosis is that existing tools and established theoretical concepts are not sufficient to describe and address the complex challenges and associated uncertainties. For example, the dominant safety model assumes that zero uncertainty is possible and understands it as a prerequisite for controlling risk. As a result, the dominant safety culture stigmatizes uncertainties, non-knowledge, lack of control and surprise and thus misses opportunities for learning (Bieder and Villena-López 2022).

For several contexts of risky technology, authors have used the experimental metaphor as an analytical lens. Bleicher and Gross (2016) analyzed the use of geothermal energy using experiments at the household level, an endeavor fraught with many knowledge gaps and potential risks. They showed that actors rely on experimental strategies (without naming them as such) when dealing with unexpected developments. The experiments' boundaries and related questions of (un-) certainty are continuously negotiated and refined by raising new questions, e.g., on observed temperature anomalies in city centers, questioning definitions and drawing further actors in. The authors found evidence that actors develop an attitude of awareness that allows them to broaden their horizon of expectation and be open for unexpected developments and willing to change strategies when needed. Furthermore, they focused on the question of learning and knowledge transfer and identified two modes of decision-making for incorporating locally-generated knowledge into the overall process of energy transformation: in the *expert mode*, new findings are directly taken into account and adjustments are undertaken in short time; in the *administrative mode*, decisions are taken based on standardized criteria and guidelines. New knowledge is taken up rather slowly.

Parotte (2020) applied the experimental metaphor as an analytical lens in a case of high-risk industry—the study of the activities of Radioactive Waste Management Organizations (WMO). Due to related uncertainties, non-knowledge and ambiguities, she conceptualized the search for a nuclear waste repository as real-world-experiment. This perspective allowed her to identify two different mindsets of the experimenting organization which both come into play (to different extents) in the search of nuclear waste repositories: an *open mindset* that integrates elements of surprise and complexity and allows for changes of initial plans and a *closed mindset aiming* to control the results of action. Parotte showed that for technical and safety aspects all analyzed WMO had a tendency for a closed mindset. For some organizations she revealed how an open mindset made it possible to include moral arguments and broader (non-expert) perspectives into the deliberative process related to the intended program of the waste depository, but also required the modification of plans. In some of the cases she analyzed the concept of reversibility was introduced in plans and concepts, triggering an open attitude.

Felt (2017) analyzed the period that followed the Fukushima accident as a real-world experiment. The experiment as analytical lens allowed her to better understand how the space defined as a laboratory has continuously been redefined according to new knowledge and which diverse actors and different types of learning were involved in these activities that finally aimed to regain control over processes. She showed how the continuous redefinition of space enabled a more fluid handling of the notions of containment and control which are central in the nuclear industry (Felt 2017: 176).

These research projects reveal that taking experimentation as a lens to analyze organizational structures and processes allows the identification of existing elements (mindsets, strategies, routines, notions, etc.) that are favorable for dealing with uncertainties, non-knowledge ambiguities and complexities. The introduction of new notions such as reversibility and the different handling of notions such as containment allowed for alternative action while maintaining control.

The experimental metaphor as an analytical tool could be applied to cases described in this volume. An analysis of the case of Groningen (see Postmes, this volume), for example, could be of interest to understand if and how industry takes induced earthquakes as an opportunity for learning (the denial of the causal link between gas extraction and earthquakes seemed to have prevented knowledge generation); how local knowledge and perspectives are handled by powerful actors (knowledge and experience of local residents, e.g., on psychological stress, was not taken into account by the gas industry and politics); or whether new knowledge is shared with the local population and with policymakers (the gas industry did not communicate in a transparent and proactive manner).

Applied to the case of small modular reactors in Canada (see Iakovleva, Coates and Rayner, this volume), plans for installing the technology could be analyzed by using an experimental perspective. Such an analysis makes it possible to identify if routines are put in place that allow for the creation of new knowledge and for systematic learning processes that include knowledge beyond expert knowledge in industry and policy (e.g., neighbors' and public's experiences). In addition, fuel (uranium) production and waste disposal probably should be understood as part of the collective experiment and thus should be included in considerations using an experimental lens.

4.4 Experimental Design to Maintain Safety in Transformation—A Next Step

An analytical experimental perspective makes it possible to identify and understand if the capacity of structures, processes and state-of-the-art approaches in risk assessment and safety management supports dealing with unforeseen developments and ambiguities and to use them in a productive way for learning and knowledge production. While researchers have attributed the experimental metaphor to contexts of high-risk industry for analytical purposes, the author of this chapter is not aware of a case of explicit experimental organization of industrial projects, concepts or processes (similar to urban laboratories).

Several authors have stated that experimental designs do not prevent the occurrence of adverse developments, but by focusing on continuous knowledge production and adaptation to new and changing circumstances, combined with the acceptance that it is impossible to know everything one hundred percent in advance and the acceptance that things (strategies, plans, actions) can fail, they deliver more robust results and allow for management in highly uncertain situations (Gross and Hoffmann-Riem 2005; van de Poel et al. 2017a; Bulkeley et al. 2016). Existing research has shown that an attitude of preparedness and awareness on the part of the actors and institutions involved is a prerequisite for building and using an experimental design (Overdevest et al. 2010). It allows for adjustments, the provision of resources needed for adjustment and adaptation, and thus preserves the ability to act (Parviainen et al. 2021).

Thus, analyses using an experimental lens reveal points that might serve as a starting point for explicit experimental design in the context of high-risk industry—an appropriate legal framework, application of new notions such as reversibility, or a different understanding of stakeholders' role. It remains however a task for future research projects to test such an explicit experimental organization in the context of high-risk industry.

The case of Stavanger (see Engen and Morsut, this volume) seems to be a case that might be designed in the form of an experimental setting. The problem of regional transformation and economic change related to the transformation of the oil industry is highly complex and uncertain and will affect the inhabitants and institutions in the area. The multiple dimensions of the transformation—economic, social, but also environmental (due to sea level rise)—could be addressed in an experimental design that integrates actors beyond government and industry in collaborative knowledge production early in the process. Non-experts such as local residents or local businesses are important participants because they will have to deal with new technical and organizational structures in their daily lives. Residents could be encouraged to contribute their own ideas and implement them in small projects on a trial basis, e.g., to test possibilities of alternative means and practices of transportation, and local economic actors beyond the oil industry could participate and try out new business fields. An experimental design would allow for such trials by defining the overall structure and rules accordingly, actively taking into account the legal framework (e.g., Parotte 2020).

In the experimental design, the progress of the projects would be regularly monitored and readjusted if necessary. Projects that fail would not be considered negative failures, but their analysis would provide valuable information on the reasons and allow conclusions to be drawn for adjustments. In terms of research and practice on risk and safety issues, particular emphasis should be placed on safety issues, such as the vulnerability of new infrastructure designs. Safety-related issues should be addressed early in the process and kept in focus during the process in order to identify and respond early to unexpected developments and to integrate emerging issues.

4.5 Concluding Remarks

An experimental perspective seems to offer advantages in dealing with uncertainties and unexpected developments in tackling transformative challenges in the area of risk and safety in industry and related to infrastructures. As van de Poel (2016) argued, an experimental approach for implementing new technologies is a possibility to deal with the control dilemma of technology development. Existing research reveals that an experimental lens as *analytical perspective* is useful to identify favorable structures, processes and mindsets. Such a perspective does not in itself require change, e.g., of organizational structures or structures of projects, but it can provide the basis for such a change and serve as a starting point for the explicit establishment of (collective) experimental designs that facilitates learning to improve safety for the management of high-risk industries and critical infrastructures.

Using the *experiment as a design* principle in proactive way could be a further step. However, it is demanding because it involves changes of existing processes and structures or setting them up in a new manner. Although there is no general contradiction between a safety orientation and the experimental approach (see Parotte 2020), an experimental design is challenging because it fundamentally questions established beliefs, such as the culture of zero risk and of controlling everything. It takes time to develop a shared understanding of the experimental approach. Actors need to develop an attitude of openness to uncertainty, and institutions need to provide structures and routines that allow for transparency and collective learning, which includes engaging actors also against existing resistance (e.g., economic interests, interests in preserving knowledge gaps).

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Chapter 5
Safe Transitions in Complex Systems

Methods of Investigating the Interplay Between Safety and Sustainability

Johannes Weyer

Abstract Complex systems, including energy and transportation systems, constitute a crucial part of modern societies' critical infrastructure. It is imperative to ensure their stability even during periods of crisis or fundamental transformation, such as sustainability transformation. It is difficult to anticipate how individuals will respond to policy interventions aimed at preserving stability, for example, by banning cars from congested roads, or to policy interventions aimed at fundamentally altering the system, for instance, by promoting renewable energies. A conflict of interest may occur at both an individual and institutional level if sustainability measures, such as increasing the number of electric vehicles or photovoltaic systems, jeopardize the stability of the system, for example, by increasing grid volatility. Furthermore, research into complex systems has demonstrated that they tend to develop nonlinearly rather than linearly, making them difficult to predict. Agent-based modeling (ABM) has emerged as a valuable method to comprehend the dynamics of complex socio-technical systems. Moreover, ABM enables us to anticipate future outcomes and evaluate the effectiveness of different policy measures aimed at enhancing safety or promoting sustainability (or both). The chapter briefly introduces the ABM concept and the SimCo simulation framework, developed at TU Dortmund University. SimCo is grounded in analytical sociology, focusing on people's everyday practices, bounded-rational decision-making and on governance concerns. Additionally, this chapter will present the outcomes of several simulation experiments to address the question of how to achieve safe transformations of complex systems.

Keywords Agent-based modeling · Computer simulation · Socio-technical systems · Artificial societies

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5.1 Transformation of Critical Infrastructure Systems

Complex systems, such as energy or transportation systems, constitute vital components of modern society's critical infrastructure. It is imperative to maintain their stability, even during times of crisis or significant transformation, such as sustainability transformation (Orwat 2011; Engen and Morsut 2023).[1] The transition to a sustainable state presents a complex issue, as safe and reliable operations must be guaranteed not just after the transition, but also during the phase of coexistence between old and new elements, such as electric vehicles and cars with combustion engine or electric generation devices operated partly by fossil fuels and partly by renewable energies.

Hence, uncertainty prevails during this transition period, and it is challenging to foresee individuals' actions and reactions toward changing circumstances or political interventions, as well as the system dynamics that may result from uncoordinated individual actions. Will a substantial number of people opt for electric cars or heat pumps and thereby inadvertently cause increased volatility risks to the energy system? Will there be sufficient charging stations for electric vehicles, and how many will be required during each phase of the transition? The availability of charging stations (and affordable charging rates) may prompt individuals to consider buying an electric vehicle. However, the low demand for EVs could hinder providers from installing charging stations if there is no economically viable business case. This situation resembles the classic chicken-and-egg problem. Similarly, how many privately owned and operated photovoltaic devices can be integrated into the electric grid while simultaneously feeding in large amounts of electricity on a sunny day?

Numerous tensions can emerge between safety and sustainability, as well as between stability and change (Nawaz et al. 2019; Agora Energiewende 2019). To manage distributed systems effectively in the future, sophisticated real-time governance measures will be necessary (Weyer 2019). For instance, demand-side management of energy grids can balance out supply and demand based on the available capacities in power consumption and production (Paulus and Borggrefe 2011; dena 2012).

5.2 A Sociological Perspective

The queries posed above could be addressed solely by engineers. However, since the dynamics of complex infrastructure systems depend not only on technical parameters but also on people's actions, a sociological viewpoint might help to comprehend the social dynamics of complex socio-technical systems. Some individuals may behave as early adopters, swiftly embracing new options, while others may resist rapid

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[1] Considering the three dimensions of sustainability, this term signifies not only ecological sustainability but also economic viability and social equity. However, this contribution will concentrate on methodological concerns without delving into those specifics.

change or opt to wait before adopting novel alternatives. Most reports cited above do not consider the role of human behavior but instead rely on aggregated data, such as load profiles in the energy grid.

The question at hand is how to assess or predict the ability to execute sustainable transitions that uphold safe and reliable operations, particularly during critical phases that involve numerous uncertainties. Is it possible to peer into the future and assess the effective functioning of complex socio-technical systems with respect to sustainability, safety and reliability?

5.3 Agent-Based Modeling of Complex (Adaptive) Systems

Agent-based modeling (ABM) has emerged as a novel approach to studying the structures and dynamics of complex, adaptive systems, including the economy and climate (Resnick 1995). ABM permits the creation of artificial systems on a computer screen and experimentation with various what-if scenarios. Running a complex system on the computer enables the observation of nonlinear interactions, their impact on system dynamics and possibly the chaotic behavior of systems that evolve unexpectedly and instantly enter a new and irreversible state (Richter and Rost 2004). Compared with real-world experiments (cf. Bleicher 2023), this approach avoids endangering society and helps coping with uncertainties by evaluating sustainability transformation strategies *before* their implementation.

An illustration from climate research demonstrates a feedback mechanism, which arises from nonlinear interactions and ultimately leads to an irreversible process (cf. Fig. 5.1).

Global warming results in increased temperatures, particularly in regions like Siberia where permafrost soil thaws and emits additional greenhouse gases, exacerbating global warming. At certain tipping points, these processes accelerate in a self-dynamic way and become irreversible. Such developments cannot be comprehended solely through linear thinking but require concepts from complexity research.

Similar effects may arise in socio-technical systems, such as traffic congestion or energy system blackouts, which are nonlinear results from the aggregated behavior

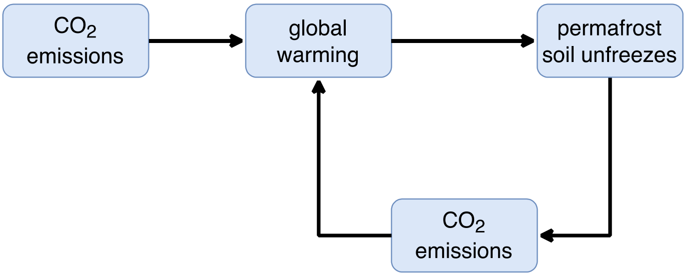

Fig. 5.1 Nonlinearity—the example of permafrost soils. *Source* Author's own work

of numerous individual actors. No actor intentionally causes these effects, but rather contributes to them through their individual decisions, such as purchasing radiators to cope with high gas prices during the current energy crisis.

5.4 ABM of Socio-technical Systems

Social scientists have also adopted this method to investigate the dynamics of social systems, such as the spread of rumors, infections or innovations (Epstein and Axtell 1996; Van Dam et al. 2013; Weyer and Roos 2017). Agent-based modeling (ABM) enables the inclusion of diverse and heterogeneous social actors. Additionally, performing simulation experiments with artificial social systems allows social scientists to explore potential paths to the future and examine various policy intervention strategies.

Implementing a sociological model of a socio-technical system, such as the transportation or energy system, requires three key components:

- agents who represent typical actors and their decision-making rules;
- the contextual framework, including social, technical, political and institutional structures that define the boundary conditions for the actions of agents;
- rules for interaction between agents themselves as well as their context.

5.4.1 Agents

Agents have properties, preferences and strategies, which resemble real actors. Data needed for modeling agents is mostly gathered by means of surveys (cf. Postmes et al. 2023). This method makes it possible to construct typical agent types, such as eco-friendly or comfort-oriented agents. With modern simulation software, one can parametrize each agent differently (referring to age, sex, income, agent type, preferences, routines, car ownership, daily tasks, etc.), so that large populations of heterogeneous agents can be generated for experimentation at the computer screen.

The decision rule in models of artificial societies is simple. When faced with alternative options, such as taking the bus, car or bike, agents select the option that best aligns with their individual preferences (Konidari and Mavrakis 2007). The concept of subjective expected utility (SEU) encompasses situational parameters, as well as personal expectations and preferences (Esser 1993; Velasquez and Hester 2013). In a comparable situation, the environmentally conscious individual would possibly opt for cycling, while the comfort-seeking individual favors driving a car.

5.4.2 Context

The so-called landscape is the second component of a simulation model, which is necessary for agents' movement. Its configuration is influenced by the area of inquiry. Typically resembling a checkerboard, an infrastructure network often consists of nodes, representing residential buildings, workplaces, crossroads, train stations, bus stops, as well as edges that connect them, like roads, bike tracks or public transport railways. Together with available technologies such as cars, bicycles, public transport, car sharing and more, this context shapes the possibilities and limitations for all individuals, offering opportunities such as nearby bike rentals, while also imposing restrictions, such as the prohibition of cycling on highways.

Every contextual element has properties, some of which are "natural", such as the maximum number of cars permitted on a residential road, and others that are politically defined, such as the limit on CO_2 emissions or the amount of city toll charged for that road. These properties provide policymakers with a significant tool for intervention, including the option to increase the city toll for combustion engine cars or, ultimately, ban their use.

The same holds true for technologies, which exhibit specific characteristics, including bikes' low pollution levels in comparison with cars as well as their lower speed. These characteristics can be altered by political policies such as implementing speed limits on cars or introducing new technologies such as the e-bike that enhances the bike's speed and range.

5.4.3 Interaction

The last aspects of an ABM include rules for the interactions between agents, but also between agents and context. In a transportation system, agents typically adhere to their individual lanes and sustain a safe distance when approaching other agents. Roads can affect agents through various mechanisms, such as speed limits or tolls. In turn, agents not only occupy a road for a short period of time, but their presence also leads to wear and tear of the road alongside polluting the environment.

Every transportation system user affects system dynamics by altering parameters such as the number of cars on a given road section. Therefore, they have an indirect impact on other users who may opt for public transport when roads become congested.

5.4.4 System Dynamics

A multitude of autonomous actions, influenced by the present system state at time *t*, leads to a self-organized system dynamic. The emergent outcomes of this process are hard to predict but make up the subsequent system state at time $t + 1$. Agent-based modeling can depict the dynamic interaction between the micro-level (agents' actions) and the macro-level (system state). The outcomes of these actions, such as traffic congestion, may be unforeseen and are not included in the agents' strategies, but emerge as a nonlinear product of their autonomous and uncoordinated actions.

5.4.5 A Sociological Perspective

This approach to modeling complex infrastructure systems may resemble the methods employed by engineers when analyzing the causes of traffic congestion (Schreckenberg and Selten 2013). Nonetheless, from a sociological standpoint, it is crucial to avoid treating human agents as mechanical components that behave identically in a perfectly rational manner. Rather, they must be regarded as conscious individuals who act in accordance with personal preferences. Sometimes, decisions may appear irrational, such as taking a car for a short one-kilometer trip. However, these everyday practices are important to consider when attempting to understand the dynamics of socio-technical systems by analyzing the interplay between the micro- and the macro-level.

Sociological theory of action and macro–micro–macro models are essential components in creating artificial societies that represent real societies, particularly in cases of sustainability transformation (Hedström and Swedberg 1996; Ostrom 2010; Esser 1993).

5.5 Simulation of the Governance of Complex Systems (SimCo)

The simulation framework SimCo has been developed at TU Dortmund University, starting in 2012. Its primary aim is to promote and advance governance research, which previously relied heavily on case studies and was limited by the "governance trap" (Grande 2012). According to Grande, this trap resulted from a lack of understanding of social mechanisms that constitute social systems and enable external influences.

Focusing on governance issues, SimCo does not address physical details, such as the dimensions and lengths of bus stops, and instead puts emphasis on social mechanisms that shape and influence individual behavior (Adelt et al. 2018). Thus, the network, representing a transportation system, comprises nodes and edges, with freely programmable dimensions (as stated above). As a general-purpose framework, SimCo aims to explain the dynamics of systems resulting from the interaction of heterogeneous agents that make autonomous decisions—and conversely, to explain agents' behavior as an outcome of their individual preferences and situational constraints. SimCo is one of the efforts to systematically translate a macro–micro–macro sociological model into an agent-based model (Esser 1993).

SimCo has been utilized for various experiments on risk management and sustainability transformation, primarily involving road transportation (Philipp and Adelt 2018; Weyer et al. 2019, 2020). Several what-if scenarios have been investigated, analyzing the effects of external interventions on the individual transport mode and route choices of various agent types. The primary outcome of these experiments is this: the most effective strategy for political interventions, such as mitigating risks of congestions or emissions and promoting system change toward sustainability, is to adopt the governance mode of soft control. This mode uses incentives rather than harsh measures such as bans that are typical of strong control (Weyer et al. 2020).

5.6 Experiments

Two experiments, one relating to transportation and the other to energy, will illustrate the value of the ABM approach. The initial experiment will highlight the relation between sustainability and social acceptance, while the subsequent one aims to examine the balance between sustainability and safety.

5.6.1 Political Regulation of Urban Transportation

Several political strategies for regulating urban transportation have been considered, including enhancing bicycle comfort (hypothesis H1), increasing the number of bicycle tracks (H2), implementing a city tax for cars (H3), introducing speed limits for cars (H4) or reducing prices for public transport (H5). These options have been examined incrementally by adjusting relevant parameters, represented on the *x*-axis of Fig. 5.2 (Philipp and Adelt 2018). This graph illustrates the effects of all five measures on (mean) emissions, represented on the *y*-axis of Fig. 5.2.

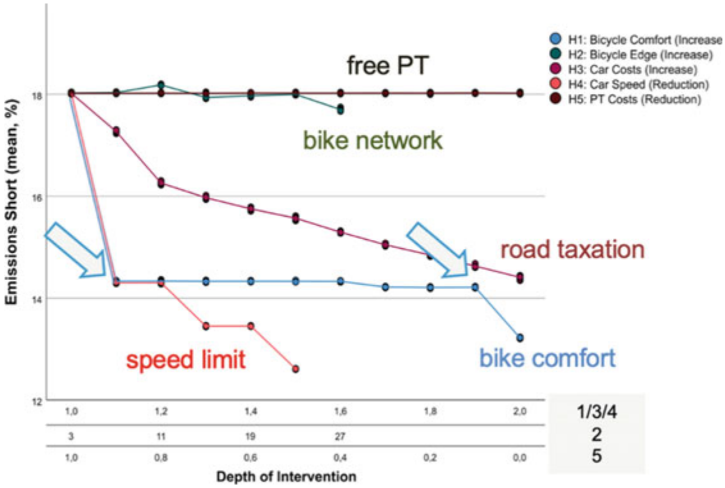

Fig. 5.2 Effects of political regulation on emissions in transportation. *Source* Philipp and Adelt (2018: 44)[2]

Furthermore, the individual satisfaction of agents in accepting the five options was measured by calculating their subjective expected utility (SEU) of the journeys traveled (represented on the y-axis of Fig. 5.3).

As depicted in Fig. 5.2, there is no discernible effect from either decreasing public transport tariffs (H5) or expanding the bicycle network quantitatively (H2). However, implementing a speed limit (H4) proves effective but faces significant challenges regarding public acceptance (cf. Fig. 5.3).

Surprisingly, a minor improvement in cycling comfort (H1), through initiatives such as bike storage facilities, traffic signal priority and charging stations, has a significant impact comparable to speed limits. In addition, these measures are relatively inexpensive and easy to implement, and public acceptance is high (cf. Fig. 5.3). Finally, a city tax (H3) is an effective measure that is more accepted than other alternatives.

However, the two tipping points (highlighted by the blue arrows in Fig. 5.2) are most intriguing as they indicate a nonlinear progression. These tipping points can be explained by the behavior of distinct agent groups implemented in SimCo. Certain agents, who have a general preference for cycling but are discouraged by the lack of comfort, immediately switch if, for instance, secure storage options are available (a 10% increase). If cycling were as comfortable as driving a car, for instance, through covered and heated cycle paths during winter and free e-bike rentals (resulting in a 90% increase), it is likely that other groups would switch, at least in this hypothetical scenario. This may be an improbable assumption, but it demonstrates the significance of a sociological perspective, which considers the diverse actions of various agent groups.

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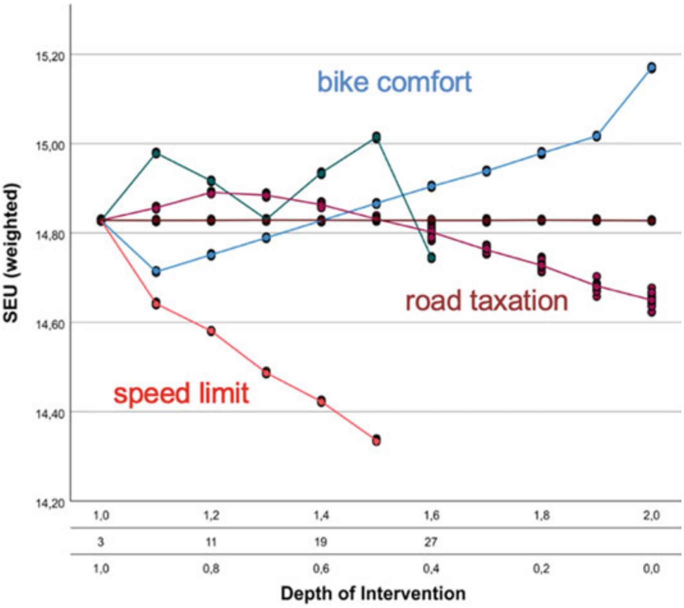

Fig. 5.3 Acceptance of various policy measures. *Source* Philipp and Adelt (2018: 46)[3]

To better understand the impact of policy measures, it is important to consider that different groups of agents may react in varying ways. This can lead to unforeseen, aggregated effects that are difficult to interpret as not all agents alter their views simultaneously.

Complex socio-technical systems typically involve nonlinear interactions, which researchers can explore by conducting experiments using computer models that are grounded in a sociological theory of action. Understanding the results of such experiments can be challenging, as they are often not easily comprehensible using linear thinking.

5.6.2 Demand-Side Management in the Energy System

The second experiment was conducted using a simulation of the power distribution grid in a small, sparsely populated residential area with 167 households comprising detached and semi-detached houses (Hoffmann et al. 2020). The agent population was composed based on existing energy end-user typologies (i.e., households). The diffusion of photovoltaic (PV) systems was assumed to be rather high in this future scenario, leading to an increase in power generation volatility (cf. Table 5.1).

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Table 5.1 Shares of end-user types and building modernization for 167 households[4]

	Agent type	Share (%)
Population	Hesitant skeptics	10
	Eco-responsible helpers	40
	Cost-conscious materialists	30
	Spendthrifts	20
	Devices installed	Share (%)
Building modernization	PV systems only	35
	PV systems with battery storage	10
	PV systems and heat pumps	5
	Heat pumps only	10
	Inflexible electricity devices only	40

Source Hoffmann et al. (2020)

Three experiments were conducted with different modes of governance: decentralized self-organization; distributed, soft control; and centralized, strong control. The latter modes represent two different demand-side management (DSM) concepts: maintaining grid stability and reducing fluctuation risks through financial or other incentives for end-users (soft control) or direct system operator access to controllable devices like PV systems, battery storages and heat pumps (strong control). In comparison, the former mode represents a base scenario of self-organization through independent and uncoordinated decisions of energy end-users.

The aim of these three experiments was to assess the extent to which interventions can enhance system stability on a macro-level. The experiments were conducted over a seven-day period, and the cumulated load of households (in kW) was used as a macro-level indicator to evaluate the effectiveness of the three modes of governance.

A two-day section of the measurement series is illustrated in Fig. 5.4. The black curve (decentral self-organization) shows a feed-in peak at noon of the first day, while no such weather-related generation occurs on the second day. On both evenings, the load increases clearly since electricity consumption is higher during this time of the day.

Interventions aimed at reducing feed-in have some impact by decreasing the total absolute value of the load and resulting in a decrease in grid fluctuations. Centralized and strong control measures exhibit slightly superior results, although differences between central and distributed control are minimal.

Figure 5.5 shows the violin plots that depict the distribution of measured values over the entire duration of seven days. These anomalies are important for assessing the stability of the grid: the interventions, regardless of their type, proved effective in mitigating outliers, i.e., peaks of low or high consumption and feed-in.

An additional statistical analysis (not included here) confirms that soft control is adequate and can enhance the stability of the local grid. A considerable proportion

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[4] Adapted from Hoffmann et al. (2020), released under a CC BY 4.0 license.

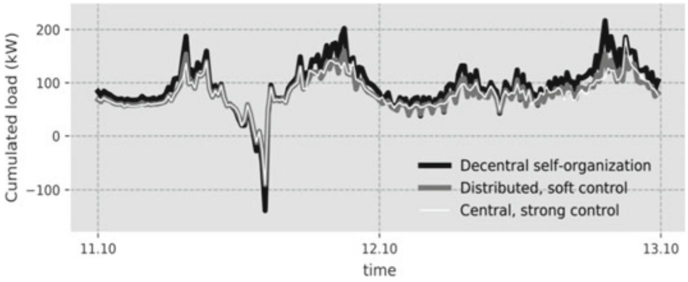
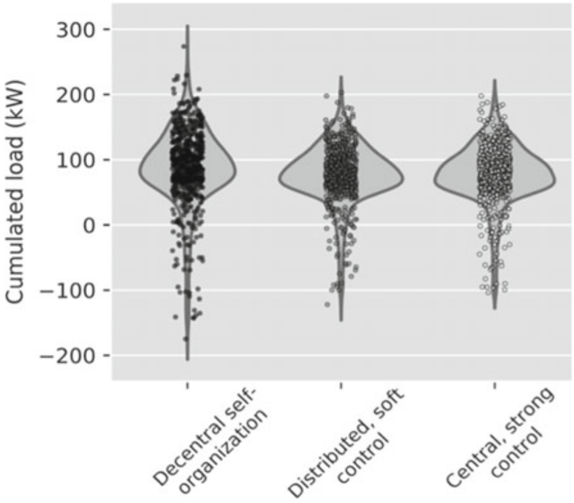


Fig. 5.4 Cumulated load in kW (two-day section) over time, comparing three modes of governance. *Source* Hoffmann et al. (2020)[5]

Fig. 5.5 Cumulated load in kW. *Source* Hoffmann et al. (2020)[6]



of end-users are willing to respond to soft interventions. Therefore, central, strong control should only be utilized in rare circumstances, for instance, when previous soft control efforts have not yielded satisfactory results, and there is an imminent danger to the system's stability.

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[6] Reproduced from Hoffmann et al. (2020), released under a CC BY 4.0 license.

5.7 Conclusion

To study the dynamics of complex socio-technical systems, it is necessary to examine not only the technical aspects but also the social components. These social components include real people and their everyday mobility and energy behavior. A sociological theory of action can be used to model these behaviors, which covers people's subjective decision-making. Other models may also be applicable. Agent-based modeling and computer-based experiments using a sociological system model could enhance our understanding of the interrelation between safety and sustainability, as well as how agents might respond to political interventions aimed at promoting sustainability.

The initial urban transportation experiment highlights the interrelation between sustainability and social acceptance. This relationship is crucial in ensuring safe operations on a broader scale. We have not calculated the number of accidents or congestion length, although it could have been done, too.

The second energy grid experiment has highlighted the requirement for establishing a balance between management approaches and behavioral adjustments to ensure safe *and* sustainable energy system operations.

ABM therefore is a valuable tool for investigating these complex issues. However, models should not be considered as perfect copies of reality, but rather simplified representations that facilitate experiments with different future scenarios—based on desired goals or states for complex systems. Consequently, agent-based modeling offers a means to test the assumptions behind these scenarios and evaluate the plausibility of transformation pathways regarding safety and sustainability.

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Chapter 6
Climate Risk at Local Level

A Systemic Risk Approach for a Reliable Transformation of a Local Industry System?

Ole Andreas Engen and Claudia Morsut

Abstract This chapter addresses how public authorities understand climate risks and their consequences in the context of a socio-technical system such as the petroleum industry in Norway. This issue is discussed by selecting Stavanger Municipality, the petroleum capital of Norway, as a case study to explore the local understanding of climate risks, in terms of physical, transition and systemic risks. Stavanger Municipality and its region are experiencing socio-economic transformations of the main industry, consisting of the redesigning of prevalent system structures and the rebranding of the Municipality from oil to energy capital. This approach is sustained by the introduction of new practices, complying with climate change considerations, without interrupting important systemic functions and services.

Keywords Climate risks · Petroleum · Socio-technical system · Transformation

6.1 Introduction

This chapter addresses how public authorities understand climate risks and their consequences for the local economy and industrial fabric. In this chapter, the local level denotes regional authorities and/or municipalities in Norway and how their comprehension of climate risks and consequent uncertainties influences the implementation of proper mitigation and adaptation strategies, which, in turn, affect the economic system in terms of transition risks. The petroleum industry is the backbone of the Norwegian economy; its very existence is challenged in the context of climate urgency: the IPCC has called for a substantial reduction in fossil fuel use and for a faster transition toward a greener economy, if the world wants to meet the targets of the Paris Agreement, adopted in 2015 (IPCC 2022). However, the petroleum industry is vital for developing regional and local communities. In Norway, in the last 50 years,

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Stavanger Municipality and its region have been the center of this economic development, which has induced the following paradox: on the one side, the revenues from the petroleum industry have provided a good basis for developing new sustainable technologies to support a greener economy. On the other side, these technologies are supported by oil and gas exploitation, which contributes to gas emissions and pollution (Engen and Olsen 2009).

The chapter will explore the following questions:

- How do local authorities in Stavanger frame climate risks?
- How can coping with transition risk be sustainable for the local economy?

Our contribution builds on risk science to explore how risks associated with climate change are understood, interpreted and tackled in the context of an inevitable transformation of an economic region, such as Stavanger (see Fig. 6.1). Technological and economic changes are general trends in modern capitalist societies. Examples such as the Ruhr district in Germany or the coal and steel region in Pennsylvania and Ohio in the USA illustrate how economies need to adapt to the market's demands and environmental requirements. In the case of Norway and Stavanger, international environmental constraints have led to an expansion of investments in renewable energy sources, such as wind and small-scale hydropower (NOU 2018; SSB 2023). This means, foremost, to reveal different kinds of transition risks associated with industrial transformation but also to address this issue in terms of systemic risk. The former implies that substantial changes in the petroleum economy could detach the Stavanger region from the economic engine of Norway, with heavy economic consequences for the local community. In general, this chapter describes a socio-technical system with huge challenges that national and local policymakers must address to cope with climate change. Transition risk management needs more attention regarding the safety implications of what a transition to a greener economy means for such a socio-technical system.

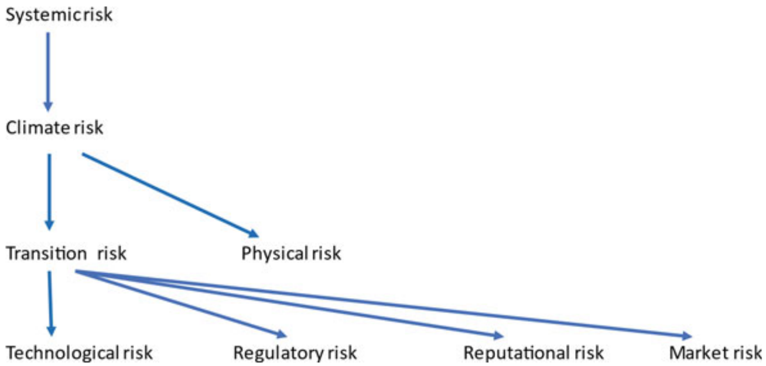

Fig. 6.1 Risk types and their relationships according to the documents. *Source* Author's own work

6.2 Conceptual Considerations

Climate risks are constituted by the wide range of risks associated with climate change (Aven 2020; Lucas 2021). They are often dynamic and unpredictable, since several systems (physical infrastructures, economies, ecosystems, societies, etc.) are impacted at the same time, leading to challenges for risk assessment and management across these systems, due to their different levels of vulnerability and exposure. In this regard, climate risks can be considered systemic risks (Li et al. 2021; Renn et al. 2020; Renn 2016), according to the following five characteristics: they are complex, transboundary and nonlinear; they lead to tipping points, and they produce a gap in perception and regulation (Schweizer 2021). Transition risks concern risks occurring in the process of transitioning to a sustainable economy, when, for example, new disruptive technologies or green finance tools are deployed (Aaheim et al. 2012; Semieniuk et al. 2021). In this case too, we can argue that transition risks are systemic: they concern states, public and private companies and international organizations, which must undergo the political and socio-economic changes needed to respond to climate change and achieve a low-carbon economy.

In Norway, national authorities have promoted the concept of climate risk through a 2018 Norwegian Official Report (NOU), titled *Climate risk and the Norwegian economy* (NOU 2018). Here, the NOU considers two types of climate risks: physical risk and transition risk. The first relates to the consequences of physical changes in the environment due to climate change. Examples are risks linked to floods, landslides, forest fires, extreme weather, sea level rise, drought, etc. The latter concerns the transition toward a low-emission society and the consequences of climate policy, technological development and associated uncertainties on the Norwegian economic system. Regardless of which understanding of climate risk one employs, physical or transitional, the concept of systemic risk seems the one indicating the most inclusive understanding of risk associated with climate change, by considering interconnectedness and "transboundariness" as central characteristics of climate risks (Challinor et al. 2018; Morsut and Engen 2022).

6.3 Findings

Stavanger Municipality is considered the petroleum capital of Norway. At the same time, the Municipality is undergoing significant socio-economic changes in adherence, for instance, with the 2016 National Smart City[1] Roadmap (Stavanger Municipality 2023a), the UN's Development Goals (2023) and the EU Mission for climate-neutral and smart cities by 2030 (European Commission 2023a). Stavanger Municipality is located in Rogaland County in southwestern Norway. In 2020, the islands

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[1] "A smart city is a place where traditional networks and services are made more efficient with the use of digital solutions for the benefit of its inhabitants and business" (European Commission 2023b).

of Finnøy and Rennesøy were included in the Municipality, which totals approximately 145,000 inhabitants (per September 2022). The merger means that Stavanger Municipality consists, to a greater extent, of forestry and agricultural soil and is, therefore, particularly exposed to climate change. Stavanger Municipality has been coping with climate risks for a long time, through mitigation and adaptation strategies. Climate change mitigation is a task within the Department of Urban Environment and Development (Climate and Environment Unit), while the Unit of Preparedness and Community Development within the Department of Urban and Community Planning deals with climate change adaptation.

To grasp the local understanding of climate risks (see Fig. 6.1), we performed a document analysis of the most recent and relevant documents, which make explicit and implicit references to risks associated with climate change:

(1) The *Municipal Master Plan* consists of a *Community Plan* (Stavanger Municipality 2020a) and an *Area Development Plan* (Stavanger Municipality 2023b). Both documents illustrate the Municipality's strategy until 2034 and 2040 respectively regarding how the city will grow and change.
(2) The *Climate and Environment Plan* 2018–2030 (Stavanger Municipality 2018) proposes mitigation and adaptation measures and actions in several sectors (agriculture, transport, water, etc.) for sustainable development, in interaction with the local community. National and international requirements and expectations to fight climate change are considered, to set guidelines for the Municipality.
(3) The *Industry and Business Development Strategy* 2021–2030 (Stavanger Municipality 2021) describes the strategy for how the local economy (mainly petroleum) needs to adjust to cope with climate change, to ensure a more sustainable business base, to further develop existing industries in a more sustainable direction and to create new industries with high value creation and employability in the region.
(4) The *Comprehensive Risk and Vulnerability Analysis* (HRVA) (Stavanger Municipality 2020b) establishes a common understanding of risks and a common societal safety and preparedness approach, necessary after the 2020 merger. The focus is on major events that can affect the safety and security of the population across sectors.

We added a fifth document, which is an analysis requested by the Norwegian Environment Agency to study physical and transition risks and to assess the local climate risk management in Stavanger, the (5) Report: *Analysis of Climate Risk for a Selection of Municipalities* (Proactima and The Governance Group 2020).

6.4 Analysis

All five documents recognize that climate change is a fact and a challenge, unfolding now and not some day in the future. Hence, acting now and not tomorrow is a necessity for the Municipality. All five share the same conclusion on which climate risks impact the Municipality: they are mainly physical risks, such as increased temperatures, more extreme weather events (storms) and sea level rise. These cause floods, landslides, lightning strikes and forest fires. The term “systemic risk” is not applied, but there is a shared understanding that climate risks have cascading effects that can be unpredictable, posing a direct danger to life and health and making it more difficult to organize risk and crisis management. Storms and heavy rains impact several economic sectors, while sea level rise erodes agricultural areas and challenges the urban development. As a result of climate change, islands and coastal areas will no longer be habitable. This, in turn, will lead to migration. In this regard, it is likely that Stavanger Municipality will experience the same climate change consequences as those observed in other areas of the world (see the South Pacific islands). In particular, the HRVA (Stavanger Municipality 2020b) underlines those critical infrastructures, like electricity lines and economic services, that are most likely to be susceptible to disruptions as a result of extreme weather. The HRVA (Stavanger Municipality 2020b) also mentions drought, which can induce electricity shortages. All five documents refer to international agreements like the UN’s Development Goals and the Paris Agreement. Despite the high uncertainty related to the local effects of climate change, all five documents propose guidelines, strategies and measures to cope with climate risks.

Quite naturally, the *Industry and Business Development Strategy* 2021–2030 (Stavanger Municipality 2021) considers mainly transition risks, while the *Report: Analysis of Climate Risk for a Selection of Municipalities* (Proactima and The Governance Group 2020) is a case in itself, since the Norwegian Environment Agency requested a study on both physical *and* transition climate risks.

According to *the Industry and Business Development Strategy* (Stavanger Municipality 2021), the Municipality needs to take into account the increasing socio-economic costs related to national and international requirements to achieve a low-emission society. The Strategy underlines that the local industrial development toward the green shift inevitably bears transition risks. The transformation of the petroleum industry will challenge the local economy. At the same time, the transformation of activities associated with the petroleum industry will affect other related industries that operate within this sector, such as the supply and service businesses. In turn, this will lead to substantial demographic changes for the economic and social structure of the Municipality. Accordingly, Stavanger Municipality will deal with challenges in terms of higher unemployment rates, development of new skills, education and so on. In the long term, new business activities must replace companies working for the petroleum industry, for instance, different types of service companies, to be able to maintain employment (Proactima and The Governance Group 2020).

On the one side, it is clear that international obligations (see the Paris Agreement) and increased political pressure require a transformation toward a greener and more sustainable local economy to cope with physical risks. This means that the more Stavanger Municipality addresses these risks, the more the Municipality will experience an increase in transition risks, with the associated economic consequences. On the other side, Stavanger Municipality (and Norway as such) expects a decrease in investments in the petroleum industry (SSB 2023). *The Industry and Business Development Strategy* (Stavanger Municipality 2021) seeks to address this dilemma by proposing to use the know-how accumulated over 50 years of technological development within the petroleum industry, combined with the long tradition in power production and mechanical industry, to develop new and innovative technologies that support the green shift and sustainable development. Thus, among other things, a way to tackle this challenge rests in developing Stavanger Municipality as a Smart City, by promoting new technologies to enhance the green shift.

Indeed, some of the actions proposed by both the documents forming the *Municipal Plan* (Stavanger Municipality 2020a, 2023b) carry some features of a Smart City. Besides promoting a path of sustainable growth and development, by facilitating a short-traveled everyday life, making it easier to walk, cycle and travel by public transport and adopting nature-based solutions, the two documents aim at strengthening cooperation with business and research, to develop smart solutions, and facilitating renewable energy solutions, to be in the forefront of the development of new and sustainable technological solutions. The documents contain references to the economy of the Municipality being mainly driven by the petroleum industry, and the ambition here is to reduce 80% of the greenhouse gas emissions by 2030 and become fossil-free by 2040. However, how to reach this ambitious goal in practice and which socio-economic costs the Municipality will endure are not explained. Some answers can be found in the *Climate and Environment Plan 2018–2030* (UN's Development Goals 2023). The document is built around local climate-related challenges, goals and concrete responses needed to tackle climate change until 2030. The focus is on how to reduce emissions of greenhouse gases from road traffic, cruise tourism and energy use in buildings, industry and plants. Around 52% of greenhouse gas emissions in Stavanger come from road traffic, with around 11% from stationary energy, i.e., energy used for purposes other than transport. Hence, the document proposes solutions to drastically reduce emissions related to road traffic, by promoting an urban development coordinated with the transport policy. One of the responses consists of the electrification of the transport sector and new renewable and smart energy solutions in the context of the Stavanger Smart City initiative. However, these measures for reducing greenhouse gas emissions carry transition risks, which are not identified or assessed.

The *Report: Analysis of Climate Risk for a Selection of Municipalities* (Proactima and The Governance Group 2020) is a very useful document for understanding the physical risk and transition risk for Stavanger Municipality. The *2020 Comprehensive Risk and Vulnerability Analysis* (HRVA) (Stavanger Municipality 2020b) has been employed here, as it has already identified physical climate risks, but the Report offers a more nuanced definition, by distinguishing acute from chronic physical climate risk according to the speed of development of the climate risk. Acute physical risk concerns, for instance, extreme weather, while chronic physical risk refers to long-term changes in weather patterns that can lead to, for example, sea level rise. Another way to describe physical climate risk is in terms of climate change's direct and indirect effects, taking into consideration the proximity of the risk. Examples of direct effects are increased costs for prevention of infrastructures or their maintenance and repair. Indirect effects occur when physical climate risk originates elsewhere but has cascading effects in the Municipality. For instance, the rise in temperatures provokes the melting of the Arctic, with a sea level rise that will touch the coastal line of Stavanger Municipality.

In addition, the *Report* (Proactima and The Governance Group 2020) seeks to offer an encompassing definition of transition risks by deepening the meaning: there are transition risks associated with municipal sectors and functions and others associated with business (mainly the petroleum industry) and their consequences for the Municipality. On the one side, political changes, new regulatory requirements and new technologies to fight climate change have a cost for the Municipality, which, for instance, has to improve the water and sewage system or make the transport system more sustainable. In the *Comprehensive Risk and Vulnerability Analysis* (HRVA) (Stavanger Municipality 2020b), the same sectors subject to these transition risks are also impacted by physical climate risks. On the other side, transition risks concern mainly the petroleum industry, which has to reconsider business activities, follow more sustainable and greener standards and meet the international obligations about emissions and the green shift. As it is, today, the industry with the highest employment rate and highest wages, transition risk has the biggest impact on the petroleum industry, with effects on the whole supply chain and Stavanger Municipality as well, with fewer high tax-paying residents, for instance. Higher capital costs and higher production prices to address the green shift could exert significant pressure on the petroleum industry, which will have a significantly reduced place in a low-emission society. The *Report* (Proactima and The Governance Group 2020) calls for faster transformation of the industry along the lines proposed by the *Industry and Business Development Strategy 2021–2030* (Stavanger Municipality 2021).

Another way proposed by the Report (Proactima and The Governance Group 2020) to define transition risks is to consider which societal sector is impacted: there are, thus, a regulatory risk, a technological risk, a market risk and a reputational risk. The first one concerns regulations that can bear unforeseen risks: for instance, an increase in the carbon tax, decided by an EU regulation, can hamper competition, since companies with fewer resources may struggle to implement the carbon tax. The second relates to a sector's use of new technologies, which can lead to unforeseen vulnerabilities by increasing the interdependence of the power supply, for instance. The third one refers to impacts on the market, as some companies are able to make investments, whereas others are not. Finally, reputational risk refers to the possibility that companies or sectors may not be willing to follow the rules regarding transition toward a low-emission society, boycotting the process.

Figure 6.1 summarizes the understanding of various types of risks applied in the documents and the relationships between these risks.

6.5 Final Remarks

By focusing on Stavanger Municipality, this chapter sheds light on how different types of risks related to climate are understood in official policy documents and how strategies are developed to cope with these risks. Based on the content of these documents, we argue that Stavanger Municipality is aware of both the physical climate risks and the transition risks that need to be addressed to reach the goal of a low-emission society. However, it does not seem that Stavanger Municipality sufficiently realizes that climate risks and transition risks are systemic risks. Nonetheless, the Smart Cities concept has been adopted by Stavanger Municipality as a strategy to combine technologies, the mobilization of citizens and business activities to work together to achieve a more sustainable way of living. In this sense, it is, however, reasonable to suggest that Stavanger Municipality, to some extent, has understood the complexity and interconnectedness of climate risks but needs to fully acknowledge this by analyzing risks as complex, transboundary and nonlinear, leading to tipping points and producing gaps in perception and regulation.

In taking Smart City as a response to systemic risks, this response could integrate the following *modus operandi*: a long-term and comprehensive strategy, whereby the Smart City approach is encompassed in both urban and economic development; drawing upon available technologies to increase cooperation and sharing of knowledge across sectors; the formulation of cross-sectoral risk and vulnerability analyses and planning; inclusive processes where the needs of citizens and local communities are at the core of decision-making; more efficient and sustainable use of resources to improve the quality of life of citizens; and, at the same time, contribute to economic development that does not damage the environment and climate, through the smart use of technology. But, most of all, Stavanger Municipality needs a substantial transformation of its main industry, consisting of the redesigning of prevalent system structures and the rebranding of the Municipality from oil to energy capital. This approach is sustained by the introduction of new practices, complying with climate change considerations, without interrupting important systemic functions and services.

This transformation is the ultimate challenge, due to the paradox that it carries: on the one side, it is the petroleum industry that provides the basis for new sustainable technologies to support a greener economy. On the other side, oil and gas exploitation needs to continue, to benefit from these revenues, but this goes against the international requirements for a substantial reduction in fossil fuel use. Then, Stavanger Municipality uses these new technologies to cope with physical climate risks to be greener and more sustainable, but at the same time this impacts the petroleum industry, increasing transition risks. However, the goal of Norwegian petroleum politics is not to dismantle the entire petroleum industry, but to restructure the sector toward more climate-friendly technology, such as carbon capture, electrification of the petroleum platforms and financial support to develop renewable energy.

To conclude, the climate and transition risk approach of Stavanger Municipality is characterized by adaptation, rather than a systemic risk policy that would mean a dramatic transformation of the entire petroleum socio-technical system. Still relying on the knowledge, technology and innovation capacity of the petroleum industry is a form of adaptive strategy that may appear slow and incremental. Such an adaptive strategy can, in the longer run, become a real existential threat for society in general and suggests that the transition risk understanding of Stavanger Municipality is concealing, rather than revealing and enlightening, when it comes to climate change threats.

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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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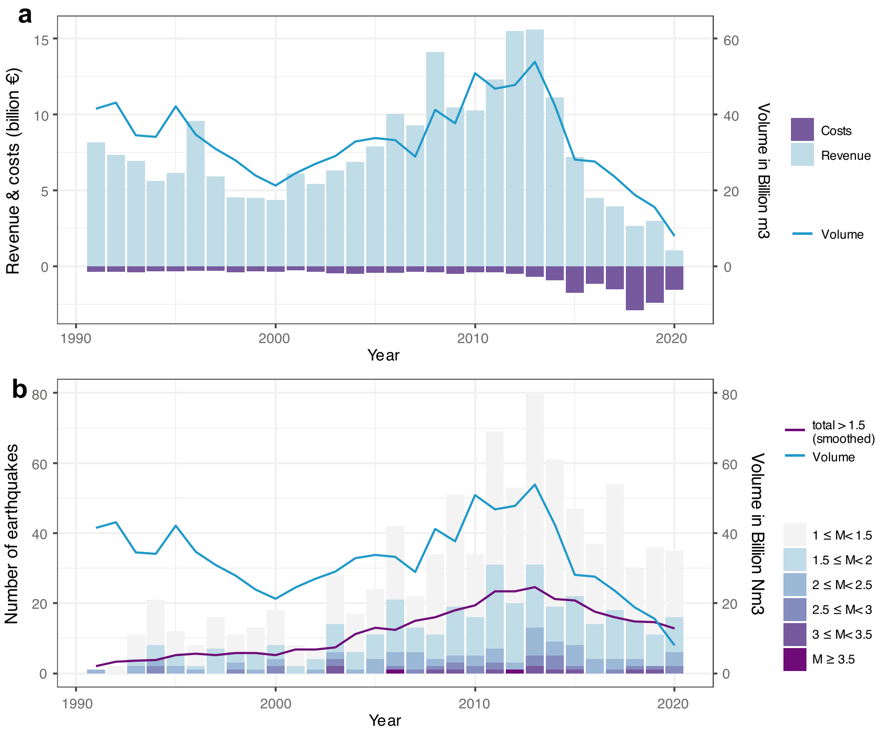

Fig. 7.1 **a** Revenue and costs from the Groningen field, at 2020 price levels. The blue line shows the annual gas production in billion cubic meters (bcm). Drawn from data derived from Been (2022). **b** Evolution of seismicity in Groningen. The bars show the annual number of earthquakes in different 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.

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[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

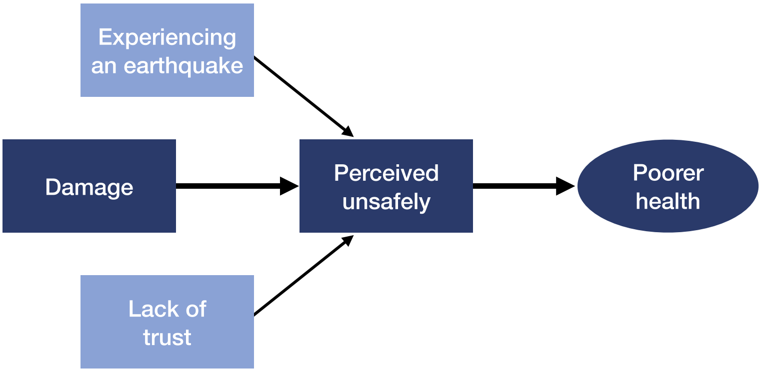

Fig. 7.2 Illustration of the relationship between exposure to earthquakes and damage, perceived trust, perceived unsafety and health outcomes in statistical path analyses (Stroebe et al. 2021)

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.

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[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.

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Chapter 8
"Old Is Gold?"

Nuclear Safety in the Face of Climate Change

Stéphanie Tillement

Abstract Climate objectives, as well as the recent objectives of energy sobriety and security in response to crises, have underpinned a call for the urgent development of nuclear generation capacity. At the same time, recent events have highlighted fragilities in nuclear infrastructures, both in their operation and in their design and construction. This chapter focuses on the French case to examine the conditions under which the nuclear industry can provide an appropriate response to climate change, as well as the risks and vulnerabilities associated with a nuclear revival. In particular, we analyze the two regimes at the heart of this revival: the extension and the acceleration regimes. We show that the interplay between nuclear power and climate change calls into question the social and temporal scales at which risks need to be defined and governed.

Keywords Nuclear infrastructures · Safety · Climate urgency · Time · Scales

8.1 Introduction

On May 16, 2023, the French Parliament officially passed a new law (Nuclear Acceleration Act) aimed at accelerating administrative procedures for the construction of new nuclear reactors, of the EPR2 type, as soon as 2024. Concurrently, the intended change in French nuclear safety doctrine and organization—the merger of the ASN (Nuclear Safety Authority) with the IRSN (Institute for Radiation Protection and Nuclear Safety)—was temporarily rejected.

Climate goals, as well as recent objectives of sobriety and energy security in reaction to crises, have supported a call for an urgent development of nuclear production capacity. Meanwhile, recent events have highlighted (unsuspected) fragilities in nuclear infrastructures, concerning both their operation and their design and construction. In the Summer of 2022, France had 32 out of 56 nuclear reactors shut down, a record number. This unprecedented situation has raised fears about energy security

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in a country that still had 69% nuclear power in its electricity mix in 2021. Many contingencies and disruptions have combined to lead to this situation. The COVID-19 crisis was partly responsible for delays in planned maintenance outages. Stress corrosion cracking was fortuitously discovered on safety equipment of the most recent reactors (P'4 and N4 series). This led the operator EDF to shut down 12 reactors in order to carry out extensive checks to assess whether stress corrosion was a threat to nuclear safety. Design and construction projects have been halted or significantly delayed, preventing them from compensating for the drop in production. Extreme climatic events have added to this, with a record number of heatwave days and severe drought. Low water levels in rivers used to cool the reactors led to a reduction of nuclear power production. For those who were not yet fully convinced of the acuteness of the problems to come, 2022 was a powerful reminder. Experts agree that this situation, previously considered as exceptional, will unfortunately become the norm (IPCC 2021). Anticipating and preparing for the consequences of climate change on the operation of high-hazard organizations (including nuclear power plants) has thus become urgent.

The situation of French nuclear infrastructures is an exemplary case of how economics, politics and technical and environmental contingencies interact and affect safety and climate goals. It also highlights how latent shortcomings and normalized forms of deviance (Vaughan 1997) combine with crises and their side effects. Drawing on the case of the French nuclear industry—and its long-term trajectory of operation and development—this chapter aims to open a conversation about the interplay between safety and climate change challenges when it comes to nuclear power plants. This problem can be tackled in two ways:

1. How may climate change affect the functioning of nuclear infrastructures?
2. How can nuclear technologies best contribute to climate change mitigation?

The first question involves analyzing the many imperatives that these systems should meet and how they can (or not) be articulated, in the short and long terms. In particular, it questions whether nuclear safety should always be treated in a relatively isolated way or whether this imperative could be articulated with others, such as production and security of supply, in a more integrated risk governance approach. The second question entails examining which technologies and innovation regimes (exploitation/exploration) are most likely to contribute effectively and rapidly to decarbonization and GHG reduction, in the face of the climate emergency.

8.2 From Nuclear Risks to Climate Risks: Toward a “Nuclear Renaissance”?

Civil nuclear power is emblematic of the risk society that emerged with modernization (Beck 1996; Lockie and Wong 2018). Its history has been marked by three major accidents, which have rekindled concerns about the use of nuclear technologies[1] (Perrow 2011). The most recent one, Fukushima, fell into the category of “Natech” accidents that “are seldom purely natural or technological” (Knowles 2014, cited in Verma 2021). It forcefully revealed the vulnerability of these “ultra-safe” systems to extreme climatic events, an increasingly serious threat with climate change. While experts used to consider as very low the probability of a natural disaster causing an industrial disaster, they now agree on the importance of being prepared for such a combination of natural and industrial events, in a cascading effect. The French nuclear industry did not wait for the summer of 2022 to think about the effects of climate change on the operation of nuclear facilities. The particularly critical 2003 heatwave prompted nuclear safety experts to assess the vulnerabilities to extreme weather events and ways of dealing with them. Fukushima has further reinforced this concern. Safety authorities asked operators to assess the risks induced (among others) by natural hazards on existing and future nuclear facilities and to propose measures in order to prevent or protect from them.[2]

On the one hand, socio-environmental changes worldwide induce new vulnerabilities that challenge traditional methods of risk calculation, management and governance. Rather than treating natural and industrial disasters as separate events, it calls for an integrated approach to these hazards, as suggested by the “Natech” accident concept. Beyond safety, these extreme climate events raise sustainability concerns, leading some researchers to consider that sustainability now includes safety (Kermisch and Taebi 2017). For example, the reduction in nuclear production capacity from May 2022 in response to drought and low water levels in rivers was mainly aimed at avoiding environmental pollution.

On the other hand, the fight against climate change has become increasingly central in the framing of nuclear issues. As François Jacq stated on December 7, 2022:

> Twenty to thirty years ago there were two main issues: security of supply and cost; you needed energy and you needed it cheap. A third imperative was added, relating to the climate: decarbonisation. The whole energy issue is contained in this triptych, being understood that the mix of these different concerns varies over time. (Assemblée Nationale 2023)

While the opponents to nuclear power put forward nuclear risks and unsustainability due to nuclear waste, the nuclear industry and new ecologists tend to frame

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[1] Three Mile Island (1979), Chernobyl (1986) and Fukushima (2011).

[2] At the European scale, this operation was known as the “Stress tests”. Its French equivalent is “Complementary Safety Assessment” (Evaluations complémentaires de sûreté—ECS), which defined the concept of a “Hard Core” as a set of materials and organizational arrangements to ensure the control of crucial safety functions in extreme situations.

nuclear power as a “clean and green energy” and thus as a “pragmatic response to interrelated challenges of energy independence, climate change, and resource scarcity” (Ialenti 2014). The increasing concerns about global warming and the objectives of GHG emissions’ reduction opened the way to a so-called nuclear renaissance. In 2022, the European Commission officialized nuclear power’s contribution to the decarbonization of the energy mix, awarding it a “green” label.

In the world energy landscape, France is often described as an exception. It remains the most “nuclearized” country in the world considering the share of nuclear power in total electricity production. In some years, nuclear power produced more than 80% of the total electricity, which led Gabrielle Hecht to consider that “France is nuclear like nowhere else”. This production is assured by 56 pressurized water reactors (PWRs), now known as a “generation 2” technology. They were built between 1974 and the late 1990s, under the Messmer Plan that supported a massive deployment of civil nuclear power. This industry is the third largest industry in France, with 220,000 employees. Beyond these figures, the singularity of the French ecosystem pertains to its history and the network of actors on which it rests. The main French licensees, EDF and the CEA, have been present from the very beginning of the French nuclear history, contributing to a very stable nuclear ecosystem. This exceptionalism is reflected in the governance of this ecosystem, which leans on tight and complex links between operators and the State, and hence between technology and politics (Hecht 2009).

In the early 2000s, after a phase of severe slowdown—described by some parliamentarians as a “nuclear winter”—France also believed in a possible nuclear renaissance. This hope was part of an international effort to boost R&D in the civil nuclear industry, marked by the launch in 2000 of the “Generation4 International Forum” (GIF) by the American Department of Energy (DOE), along with 12 countries (including France).[3] The emergence of the term “generation” during this forum was far from neutral: it supported an evolutionary reading advancing the idea of an almost linear and natural succession of ever safer, more sustainable and more efficient reactor generations. In France, this translated into the launch of the Flamanville EPR[4] in 2007 and ASTRID[5] in 2010, spearheading the third and fourth generations of nuclear reactors, respectively, and setting high objectives in terms of sustainability and safety. Yet, in 2019, the difficulties of the French industry became visible with two announcements a few months apart: (1) the official abandonment of the ASTRID project; (2) the severe analysis of the EPR by Jean-Martin Folz who described the project as an industrial failure (Folz 2019). These two events sounded like a major warning, tarnishing the image of the main organizations involved, primarily EDF, ex-Areva (now split between Orano and Framatome) and the CEA. This paved the way for major questions in the press and in the political and academic arenas. Was the French nuclear industry able to meet the twenty-first century’s major challenge: to give France, through its capacity to operate and build reactors, a leading role in the decarbonization of electricity production? It was no longer just a matter of knowing

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[3] See GIF Charter, 2001.

[4] European Pressurized Reactor.

[5] Advanced Sodium Technological Reactor for Industrial Demonstration.

whether the use of nuclear energy and thus the continuation of the French nuclear adventure were desirable, but whether this continuation was possible, at what price and under what conditions.

8.3 "Time Matters"

The difficulties encountered by the nuclear industry were widely commented upon. The President of the nuclear safety authority (ASN) declared in 2022 that the main source of fragility of the nuclear system was the lack of anticipation from EDF; the operators blamed the lack of long-term planning from the State; Folz evoked an unrealistic initial assessment of delays and a generalized loss of skills to explain the setbacks of the EPR. All these explanations relate to time. In the same vein, the recent *Commission of Inquiry* (Assemblée Nationale 2023) highlighted the extent to which nuclear projects are affected by the conflict between short-termism and long-termism that drastically limits the possibilities of anticipating plausible futures and planning actions (Slawinski and Bansal 2012), with huge consequences on the nuclear industry. This classical conflict translates the inter-temporal tension between "political time" (a maximum of one electoral term) and "nuclear time" (the life cycle of nuclear installations—several decades, from the decision to build a facility to its dismantling). Its major projects have faced the difficulty of resolving, in the very short term, the contradictions produced over a very long time period.

For the first time in almost 30 years, the government seems to be backing a large-scale nuclear revival, reflected in the Acceleration Act. We propose the notion of "temporal regime" as an analytical tool to explore the timing and tempo of this nuclear revival and to analyze the risks and emerging vulnerabilities it may entail. The nuclear industry's activities fall within two main temporal regimes, anchored in two narratives: the *extension regime* and the *acceleration regime*.[6] Both regimes respond to the climate emergency, but each refers to specific activities and carries its own risks or vulnerabilities (Table 8.1).

The extension regime is in line with the need to maintain the existing fleet, to "make it last" beyond the 40 years initially planned to meet the decarbonization objective, but also to supply electricity at an acceptable cost. This regime is based on a highly centralized and stable organization, involving the operator EDF that remains solely responsible for nuclear safety under the law, the nuclear safety authority and its technical support organization, IRSN. Safety is built through constant technical dialogue between these three players[7]. This highly stable system entails its own

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[6] The identification of these regimes is based on a careful analysis of the minutes of the meetings of the *Commission of inquiry on the loss of sovereignty and energy independence of France* (November 2022–February 2023). It also draws on the numerous formal and informal interviews held within the framework of the research projects conducted over the last ten years in relation to the nuclear sector (RESOH Chair, AGORAS project—Grant ANR-11-RSNR-0001—and NEEDS program).

[7] The parliament finally voted to merge the ASN and IRSN in March 2024, despite strong protests. This is likely to alter the dynamics of relations and naturally calls into question the stability of the

Table 8.1 Temporal regimes of the French nuclear industry

	Acceleration regime	Extension regime
Narrative and tempo	Urgency in the face of climate change Intermittency	Maintenance/durability Stability
Goals	Decarbonization of the energy mix Innovation/competitive advantage	Energy supply at an acceptable cost Decarbonization of the energy mix
Central activity	Innovation (design and construction)	Operation (production and maintenance)
Social organization	Mostly unstable and distributed	Mostly stable and centralized
Risks and vulnerabilities	Increasing complexity → Threats both to nuclear safety and energy security Generic or systemic defaults (e.g., SCC)	Delays and cost overruns Crises → delays → Threats both to nuclear safety and energy security

vulnerabilities. "Making nuclear installations last" presupposes an army of maintenance workers who perform very substantial work within short deadlines so as not to penalize production, while guaranteeing a very high level of safety. This, of course, implies maintaining and renewing the expert knowledge and skills of these maintainers. It also calls into question the nature of the relationships involved:

- Between the licensee and contractors, as a significant proportion of maintenance activities are outsourced.
- Between occupations within organizations: maintenance work is affected by internal tensions, notably between engineering and maintenance. These tensions, linked to a different relationship to the operation of technical infrastructures and therefore to the practices and rules that underpin their maintenance, mirror those that exist between the operator and the regulator.

They point to a major potential weakness of the extension regime, i.e., the increasing complexity of the regulatory, managerial and cognitive infrastructures of maintenance activities, at the risk of a lesser understanding of the systems by those responsible for maintaining them. The challenge is to ensure that the care given to existing installations (and their partial renewal) is part of a sustainable form of innovation, i.e., toward systems that are easier to control, hence more robust.

The acceleration regime fits in with the urgency to act in the face of climate change and endorses the framing of nuclear power as a pragmatic response to the objective of decarbonized energy production. It is materialized in the recent "French

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regime. The way in which safety will be affected by this change will be interesting to analyze over the coming years.

Acceleration Act" and mainly involves the development of a series of six EPR2.[8] Unlike the extension regime, which relies on perennial organizations, the acceleration regime unfolds within projects, thus temporary organizations. The most recent projects, EPR and ASTRID, have shown the fragilities induced by largely unstable physical, managerial (planning) and regulatory infrastructures. This contributed to the difficulties in steering and running these projects. The size and complexity of the infrastructure contributed to the failure of the EPR project (Folz 2019), in particular by preventing the simultaneous pursuit of safety and industrial performance objectives. ASTRID suffered from the CEA's pro-innovation bias, with the introduction of unplanned and unshared breakthrough innovations, making it difficult to steer and defend the project. Both projects faced the "knowledge crisis" inherent to the design profession, and particularly critical in the nuclear sector, firstly because it requires expert, distributed skills and secondly because of the intermittent nature of design and construction activities. The drop in activity following the Messmer Plan, combined with the associated illusion of overcapacity, led to an unlearning process from which the EPR and the ASTRID project (albeit to a lesser extent) suffered greatly. The inability of stakeholders (the State, the operators and the regulator) to fully acknowledge and then manage the intermittency of design and construction has contributed to the current pitfalls: projects with uncertain status, between innovation and renewal of old technologies, role conflicts between historical actors and disengagement of some. It exacerbated tensions between operators, designers and regulators, preventing them from defining clear objectives and standards, making trade-offs and evaluating performance, leading to a delegitimization of the nuclear sector.

These two regimes are clearly interdependent: acceleration and extension involve the same organizations and the same resources. All projects, be they design, construction or maintenance, are launched at the same time, which compels the nuclear industry to manage the cumulative dimension of these projects. The lack of long-term national strategic planning combined with short-termism (also denounced as an impediment for organizations to effectively address climate change issues) has deprived the nuclear system and more widely the electricity system, of its margins in terms of skills, personnel or technology, at the risk of making it more vulnerable to unforeseen events and snowballing effects. The succession of recent crises has shed light on systemic vulnerabilities. The COVID-19 crisis showed the difficulties in planning and organizing major maintenance operations on a very large scale, as well as the possible disastrous consequences of the absence of margins for nuclear safety but also security of supply in the future. The war in Ukraine highlighted the very tight coupling between nuclear plants' availability and safety and energy supply. This

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[8] The Acceleration law also provides for the development of small modular reactors (SMRs). While the EPR2 program is still organized centrally around EDF, both operator and architect, many SMR projects are led by start-ups. Private players are emerging alongside the major historical players (EDF, Orano, CEA). If SMR projects were to be developed, they would involve a more decentralized, or at least more distributed, organization, similar to those prevailing in the USA. This would be new in France and would necessarily involve changes in safety governance. As SMRs are still in the nascent stages of development, we will not discuss them in this article.

“era of disruption” (Bansal 2019) involves new risks, which emerge from and bring into play interdependencies that go beyond the scope of a given organization (i.e., between systems, organizations and institutions). Part of these interdependencies already existed but were previously invisible or simply overlooked.

These questions are of particular importance since the lack of anticipation forces the nuclear industry to operate increasingly following a logic of speed and results in increasing production pressures, which affect both regimes. All the chain of nuclear organizations is concerned, down to the contractor that employs welders, which is asked to train experienced welders in record time (3–4 years instead of 7 years). The safety literature has demonstrated the negative effect of precipitation and speed on safety performance (Blount et al. 2005). It underlines the complexity of articulating different requirements and associated (possibly contradictory) time frames, e.g., safety with climate or performance goals. While speed is often celebrated as “a synonym of good” in the face of the “sense of urgency”, some organizations that have become famous for their rapid decision-making are now equally famous for their mistakes and disastrous consequences (e.g., NASA) (Vaughan 1997).

These movements raise very important and difficult questions about the prioritization and definition of safety in relation to other imperatives: is safety still the number one priority (as reflected in the “safety first” doctrine)? And what type of safety? Nuclear safety? The latter is one of the variables (crucial of course) in the equation to solve when deciding to invest in nuclear power and to choose the best technology. While the objective is of course to design and operate safe systems, the debate is about the level of safety that can be achieved in relation to other crucial requirements. Safety, like performance, is multi-dimensional. The example of French nuclear power shows perfectly how dealing with a nuclear safety problem may generate new risks because of the close coupling between the production means and the supply system. It includes the risk of a “blackout” and its major side effects, at the societal scale, on infrastructures, transports, health … and thus on human lives.

One major stake is to redefine nuclear safety in its articulation with all the other types of safety, such as security of supply, environmental or ecological safety or health and safety at work and more broadly with sustainability and other forms of performance. This also requires a tight articulation between the extension and articulation regimes. These regimes raise essential questions concerning the care to be given to the existing infrastructures and the logic of innovation that should prevail in the choice of future technologies, i.e., the *exploitation* of known and mastered technologies or the *exploration* of new and disruptive solutions, in the hope for increased performance. The first approach has two major advantages, especially in the context of urgency: (1) they can be rapidly deployed; (2) they present far fewer uncertainties (notably unknown unknowns) than exploratory projects. The extension of reactors’ lifespan and the decisions to opt for a simplified design of the Flamanville EPR for EPR2 and to develop it in series, all point to a prevalence of the exploitation logic.

8.4 "Working Things Out": Toward a Broader and Long-Term Approach

A socio-temporal lens reveals two paradoxical consequences of the long-term trajectory of the French nuclear infrastructure: it has the peculiarity of being at the same time highly institutionalized and destabilized. The extended history of reactor operation has led to very high expectations from regulators, public authorities and civil society regarding safety, reliability and industrial and economic performance. However, the discontinuous trajectory of design and construction activities over the past decades, alternating highs and lows of activity, has led to a disintegration of skills and a weakened industrial base. New reactor projects, primarily ASTRID and the EPR, have felt within this ambiguous framework of undermined organizations subject to ever-increasing requirements.

The nuclear industry's ability to contribute positively to the fight against climate change will depend on its capacity to jointly govern different types of risk and on its degree of preparedness for emerging vulnerabilities induced by interdependencies between risks (or types of safety). This calls for a systemic approach, which is sensitive to aligning global and local scales as well as the short and long terms. It is far from simple. As put by Hecht et al. (2020), "our political systems are not at all designed to deal with these kinds of issues, especially with the election period. Everything is short-term". Developing nuclear infrastructures to meet climatic goals while ensuring their safety means first acknowledging such inter-temporal conflicts. One way to do so is probably to devote effort to long-term vision and planning. Planning can mean restricting degrees of freedom in the short term, against greater freedom and security in the medium and long term. This meets the current debate in France around "energy" or "ecological planning" and necessarily raises the question of the organizational and socio-material conditions for "effective" planning—in the pragmatist sense of a capacity to engage in relevant actions (Lorino 2018)—able to take into account the multiple requirements and to think about their articulation, notably safety/security and climate change. Neglected in the 1990s and 2000s, in a tacit agreement between the executive and the nuclear lobby, plans and scenarios are re-emerging as central tools in the face of the "energy wall" (Assemblée Nationale 2023). However, the impact of such tools depends on how they are designed, mobilized and governed and by whom. In the face of climate change, it is probably time to open them up to new players. If public debates do not appear to be the most appropriate vehicle (in view of the most recent debate on the EPR2), Parliament could play a more important role in the governance of nuclear issues, to foster inter-organizational and inter-institutional discussions (as has been the case for nuclear waste since the 1991 Bataille law).

More importantly—and the energy sector is a striking example—safety governance arrangements have to rely on detailed knowledge and consideration of the interdependencies between the means of production (which, in the case of nuclear technologies, are high-risk organizations) and the entire energy production and supply system. Following this, it is no longer possible to think at the level of one organization or even one industry. The governance of risk involves the inter-institutional scale. This opens new debates about the role of the Nuclear Safety Authority (ASN) (and its TSO, IRSN), its decisions and prescriptions. They have been revived very recently by the government's (strongly contested) decision to have Parliament vote to merge the ASN and IRSN, thereby challenging the strict separation between expertise and decision-making. The effects of this reform on the safety regime will be interesting to analyze in the years to come. For example, the ASN (and its TSO) have been criticized for being too zealous, for following mostly a bureaucratic logic while remaining voluntarily ignorant of the industrial realities (Finon 2023). Furthermore, while the independence of the Nuclear Safety Authority is unquestionable, the risks of a primacy of the conformity requirement over the safety requirement or the concordance between safety requirements and socio-economic issues are worthwhile topics for debate.

As Perrow forcefully showed decades ago, safety—and this is all the more true with other imperatives—is also a matter of aligning divergent interests and organizing power relationships. This social alignment work is due at several levels: at a meso-level (how organizational actors integrate and articulate the imperatives in their work and daily actions and decisions) and at a macro-level (aligning policymakers, regulators and industry actors' interests). It also means going beyond binary oppositions. For example, what would it mean, theoretically and practically, to consider safety as a dimension of performance in its own right and to handle it jointly with the other dimensions of performance, such as costs and delays? If the alignment work is fundamental to meet the challenges of safety and climate change, the work of contextualizing is just as important: the generic principles and global lessons have to be adapted to the local technopolitical context. In the continuation of Engwall's famous phrase, "no project is an island", no technology or industry is an island either. High-risk organizations—especially nuclear facilities—are not installed in a vacuum, but must fit into a system of interactions that brings into play numerous technical, political and social interdependencies, which goes far beyond the nuclear system alone and the present time. Meeting the challenges of safety and climate change is a matter of bridging scales.

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Chapter 9
Articulating Safety and Climate Change

Challenges and Perspectives

Corinne Bieder

Abstract With the increasing number of climate-related events and the growing public awareness of climate change and its potential consequences, new challenges emerge including for high-risk industries and the way to manage their safety. Ignoring the interrelations between the two societal stakes that are climate change and safety might lead to critical situations. This chapter identifies the questions raised by addressing the interplay between safety and climate change at both conceptual and practical levels. It also suggests perspectives for safety science and scientists to have a more significant contribution in this unprecedented context.

Keywords Safety · Climate change · Risk · High-risk industries · Societal expectations · Safety science

9.1 Introduction

Climate change and its increasing number of manifestations have become a critical concern to societies. Beyond the direct and immediate impacts of catastrophic events, some climate-related occurrences may affect the safety of high-risk industries. The concept of Natech events (Cruz and Suarez-Paba 2019) was introduced to characterize some of these events. Beyond these blatant cases, the interplay of climate change and safety turns out to raise multiple challenges, as illustrated by most authors in this volume. Ignoring the interrelations between the two might lead to critical situations, as illustrated by the Groningen case where a solution was chosen for climate-related reasons, initially overlooking safety issues and then governing safety in ways that would protect this solution in any case (Postmes et al. 2024). Conversely, focusing on safety with limited attention so far to the impact on climate change of high-risk industries leads some of these domains to be threatened in their very "raison d'être" today, like oil and gas or aviation. The evolution of societal expectations and

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political priorities might lead to open dilemmas regarding these high-risk activities. For oil and gas, for example, despite the impact on climate change, pursuing the current activities makes it possible to fund transitions toward other activities (see the Stavanger case developed by Engen and Morsut 2024). As for nuclear power, the potential safety impacts become secondary to the limited impact on climate change of this industry (see the nuclear power case developed by Tillement 2024).

At more conceptual and methodological levels, new questions emerge when it comes to addressing the interrelations between climate change and safety. Indeed, climate change leads to considering a broader scale, at planet level, that was not part of the systems, scopes and scales considered by safety science. What does safety and safety management mean in a context where existential risks such as those induced by climate change are becoming more likely? Are new approaches, methods or tools needed?

This chapter aims at structuring the different insights on the interplay of safety and climate change coming out of the NeTWork workshop on this topic gathering scholars from different disciplines, countries and working on different high-risk industries.

The first part addresses research and practical challenges raised by the articulation of safety and climate change.

The second part suggests perspectives to reach beyond current safety science limitations in fully embracing the climate change context.

9.2 Research and Practical Challenges

Climate change-related catastrophic events may seem to have a lot in common with industrial accidents. In both cases, one can refer to risks, safety and catastrophic consequences. Yet, articulating safety and climate change requires to reach beyond words and explore the mutual impacts in theory and practice. This section starts by exploring the concepts, methods and scopes used in both domains. Then, considering the new context created by the climate change urgency, it identifies new dilemas and challenges related to the interplay of safety and climate change.

9.2.1 Redefining the Boundaries of "Safety" and High-Risk Industries?

9.2.1.1 Extending the Spectrum and Scale of Consequences

Historically, in the early twentieth century, industrial safety emerged to cope with worker compensation laws that forced employers to provide compensation to their employees for harm related to work (Blake 1963). With time, the scope of safety of high-risk industries evolved to embrace other types of accidents beyond occupational ones, especially harm to people including non-workers and to goods and property. As an example, the International Civil Aviation Organization defines an accident as: "An occurrence associated with the operation of an aircraft (…) in which:

(a) a person is fatally or seriously injured (…)
(b) the aircraft sustains damage or structural failure (…)
(c) the aircraft is missing or is completely inaccessible" (ICAO 2016, p. 1).

Interestingly, some systems engineering manuals define safety as also encompassing the ability not to harm the environment (Desroches et al. 2003).[1] However, these definitions implicitly mean by the "environment" the vicinity of the industrial facility, thereby considering consequences such as toxic fluid leaks or radioactive releases. Otherwise, the simple fact of operating could not be considered safe for industries having a significant impact on the environment and climate change, and a number of industries or activities not considered as high-risk ones today would become so (e.g., agriculture, high-tech).

From a climate change perspective though, considering the consequences of activities on the environment not only locally, but also at the scale of the planet, would make sense. However, reasoning at this global scale, as deemed necessary by Le Coze (2024) and Etienne (2024), has never been part of safety science so far. Existing concepts and methods are not well adapted for it, as claimed by the two authors.

9.2.1.2 Extending the Nature and Likelihood of Hazards

A climate-related phenomenon and its local consequences can jeopardize an industrial facility's safety management strategies in place. In the example presented by Le Coze (2024), a drop in water level can lead to losing the cooling of a plant. In risk management terms, climate change can induce new types of hazards or significantly increase the likelihood of already considered hazards. A more indirect impact of climate change on the safety of a high-risk facility or activity might be the more likely unavailability of critical infrastructures on which these facilities/activities rely to operate safely, notwithstanding other possible catastrophic consequences of the unavailability of critical infrastructures on people, property and the environment.

Managing safety in a climate change context therefore requires extending the range of hazards considered, not only to new environmental hazards but also to other types of hazards possibly appearing as a result of climate change-related phenomena. It also entails keeping these conditions in mind when analyzing possible risk reduction or safety management measures. This would be a kind of extension of the concept

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[1] « La sécurité (…) est la caractéristique d'un système exprimée par l'aptitude ou la probabilité que le système accomplisse sa mission en l'absence de circonstances susceptibles d'occasionner des nuisances aux personnes, aux biens et à l'environnement » (Desroches et al. 2003, p. 36), i.e., Safety (…) is the characteristic of a system expressed by the ability or probability that the system will accomplish its mission in the absence of circumstances likely to cause harm to people, property and the environment.

of common mode failures, except that the failures would affect other facilities and services beyond the high-risk system considered.

Although safety science has already started looking into the reliability of critical infrastructures for the severe consequences they can have in case of unavailability, articulating safety and climate change makes it even more necessary to bring the two together. It is worth noting that they are already connected not only through concepts and methods, but also from a societal expectations viewpoint.

9.2.1.3 Safety of Humanity Beyond Safety of High-Risk Systems or Industries

Articulating climate change and safety leads to considering events that can be very different in nature but have similar consequences, especially harm to people, property and the environment. However, when it comes to managing the associated risks or learning to live with the associated uncertainties, it is worth getting into more details to characterize them respectively.

Climate change can induce existential risks as stated by Le Coze (2024), that is risks which concern humanity as a whole, without coming directly from an industrial facility or a given man-made system, but rather from more natural events (in turn possibly resulting from long-lasting dispersed human activities) with a wider reach than industrial risks in terms of their consequences. Although safety and climate change are often seen from a risk perspective, climate change-related risks, conversely to safety risks, cannot be associated with the (dys)functioning of an identifiable system (be it an organization, more or less fragmented, a plant, an industry …). In that sense, it escapes the existing concepts and methods related to risk management that start with the identification of the system under study.

Along the same line, existential risks like the ones possibly induced by climate change escape the very "raison d'être" of risk management approaches, that is the controllability or illusion of controllability of risks. Although the most common governance regime of high-risk industries relies on the demonstration that risks are reduced and maintained at an acceptable level by the "certified" organization, no one pretends or can pretend that climate change-related risks can be controlled by one or a group of humans.

The prism of impacts could seem more appropriate than that of risks to articulate safety and climate change. The concept of safety as the ability not to harm people, property and the environment might seem suitable. However, in safety science, whatever the theoretical approach (e.g., systems safety, HRO, resilience engineering), safety is also defined as a property of a socio-technical system that can be identified. Addressing climate change and the associated existential risks assumes a slightly different meaning of risk and safety than the ones used in safety science. It challenges one of the premises of most of the existing safety management approaches, which is the identification of the socio-technical system causing these hazardous situations.

In that respect, safety could be considered closer to the concept of sustainability, since the latter can be applied to socio-ecological systems.

9.2.1.4 Considering New Time Frames

Another question becomes more obvious when considering climate change: that of time. While the time frame considered is rarely made explicit in safety management approaches, safety management concepts, methods and theories commonly focus on short term. However, within the traditional scope of safety management, issues related to time have already been highlighted. The management of long-lived hazards and the institutional constancy it requires was already underlined by La Porte and Keller at the end of the twentieth century in relation to nuclear waste safe management (La Porte and Keller 1996). The disconnect between "political time" with short mandates and "nuclear time" is illustrated by Tillement (2024) as well as the extent to which it decreases the ability to anticipate plausible futures and generates tensions, more uncertainty and ambiguity.

The issue of the time frame considered and the focus on relatively short-term impacts/views of safety management become even more blatant when it comes to climate change and sustainability. Scientific studies have shown how today's climate change situation and manifestations result from a (relatively) long history of human industrial activities, illustrating the sometimes very long period between decisions and possible impact on climate. Furthermore, in his review of the principles and definitions of sustainability, Ruggerio (2021) states that any conceptual model intending to define sustainability should "account for intergenerational and intragenerational equity" (p. 9), which naturally involves time frames beyond the short term.

9.2.2 New Dilemas and Challenges

9.2.2.1 Societal Expectations and Governance Challenges

Despite these conceptual and methodological challenges to articulating climate change and safety in high-risk industries (and beyond, as identified earlier), both aspects naturally come together from a societal expectations perspective. Harm to people, property or the environment, whether due to climate change, industrial operations or a combination of both is still perceived as "unacceptable" by civil society.

Nevertheless, current governance structures tend to split the various stakes (e.g., safety and environment) as well as the various industries, even though the dilemmas and societal expectations reach beyond these boundaries. Tensions are common between stakes, for example, nuclear safety and energy security as illustrated by Tillement (2024). Engen and Morsut (2024) illustrate maybe more than a tension between climate change and economy in the case of oil and gas in Norway, since it raises existential questions as to this activity. Although currently recognized as impactful on climate change, it remains essential to sustain the economy and make it possible to support the transition of the region toward more sustainable activities.

With climate change-related events becoming more frequent and more impactful, risk acceptability thresholds as defined in high-risk industries regulatory requirements (e.g., aircraft certification) could be challenged as well. Indeed, these thresholds have historically been defined in comparison with other accepted risks and the risk of "natural" death. Should this latter evolve especially with climate change, acceptable levels of risks due to high-risk industries could be revisited.

9.2.2.2 More Obvious Tensions in Need of Articulation

As described in the previous sections, bringing together climate change and safety in high-risk industries highlights a number of tensions. It also poses theoretical challenges, notably that of articulating the different stakes, scopes, scales or time frames.

As discussed during the NeTWork workshop underlying this work, actions at the individual level may have an impact on global warming. Conversely, understanding what is going on in a specific plant and why requires understanding elements that go far beyond the plant itself (e.g., regulation from different countries if the plant has an international activity; energy supply; and all the other activities to which that of the plant is connected). Although this is not new and was already identified as an articulation challenge within the safety science community, what might be new is that the macro-level would today need to go up to the Earth itself with phenomena that reach beyond the disciplines involved so far in safety science. More generally, the climate change landscape exacerbates the entanglement of stakes and actors, the multiplicity of scales and time frames, the diversity of scopes and interests. As such, it expands the question of bringing together all the elements of a picture that is more blatantly than ever a complex one.

9.3 Perspectives for Safety Science and Scientists

The situation induced by climate change can be seen in different ways, not exclusive from one another and possibly partly interrelated: as a simple extension of already identified safety science challenges; as a deep reconsideration of today's fundamental assumptions underlying safety science challenging its foundations, concepts and methods; as a new area where safety science could help with some of its concepts, methods and theories; and as an occasion to question the role of scientists in a context where there seems to be a discrepancy between the urgency described by scientific results and the pace of evolution of policies and societies. This section will explore each of these options.

9.3.1 *Extending Current Safety and Risk Management Approaches*

From a risk management perspective, considering climate change in safety management requires taking into account new hazards, not only environmental ones but also hazards of other natures possibly induced by environmental catastrophes, as well as combinations of events of very different natures resulting from such catastrophes limiting risk mitigation options. Methodologically, it can be seen as an extension of methods such as global risk analysis (Desroches et al. 2016) and of concepts such as common mode failures to the identification of risk reduction measures, whereas it is currently limited to risk analysis.

To extend the safety scope to global scales including existential risks and to conceptualize the interrelations between the historical scale at which industrial risks were addressed (i.e., socio-technical systems) and climate change phenomena (i.e., planet earth), Le Coze (2024) suggests the framework of Post Normal Accidents.

Other articulations are needed as shown in the previous section, especially between stakes due to the entanglement of safety, climate change, economic, political … aspects or between time frames. Field studies (e.g., anthropological or organizational studies) or the HRO theory helps to highlight and understand the interrelations between stakes or time frames. However, they remain to a large extent descriptive approaches and are not predominant or even widely spread in the world of safety science. They are even less present in the world of safety practitioners driven by regulatory frameworks which neither require nor foster these qualitative analyses (Bieder 2022).

Although some conceptual and methodological work is still needed, another issue is that of translating these concepts and methods into practices.

9.3.2 *Reconsidering Some of the Fundamentals of Safety Science and Proposing New Approaches*

For a huge community of scholars and practitioners, safety is synonymous with good risk management (even though risk management only addresses the domains of the known and knowable, leaving the unknowable apart (Desroches et al. 2003)). One of the premises of risk management and risk science is that risks can be controlled and governed. As illustrated by Postmes et al. (2024), the definition and assessment of risks can be strong instruments of power. For systemic and existential risks, more global in their consequences, but also more diffuse in their origins in the sense that they cannot be associated with a particular system or an identified governance body, the fundamental assumption of risk controllability and governance is challenged. Indeed, they entail all sorts of uncertainties beyond the stochastic one considered in risk management.

Besides conceptual reworking, it would be critical as suggested by Etienne (2024) to challenge safety science's lenses and focus to put risk management in a wider context that includes many implicit assumptions regarding the overall context. Unveiling all the aspects that safety scientists and practitioners take for granted from an economic, social, political and other standpoints and exploring whether they might be challenged by climate change-induced new conditions would be needed. For example, would insurers still be able to insure for natural events; would rescue services still be able to intervene on a high-risk site after a Natech event …?

From a methodological point of view, Bleicher (2024) suggests exploring other approaches than risk management and traditional governance, such as collective experimentation. According to the author, such approaches allow for more inclusion and openness to surprise. As such, they could be a way to reach beyond the illusion of control.

9.3.3 Climate Change Challenges: An Area Where Safety Science Could Help

Uncertainties, complexities, controversies and crises develop with global warming and its growing number of manifestations worldwide. These phenomena have been studied and addressed by safety science for decades, notably through the development of theories such as HRO, normal accidents and crisis management. Systems thinking, coupling, disaster studies, resilience, governance and management of uncertainty are domains where significant knowledge has been produced by safety science (Perrow 1999; Boin 2008; Dekker 2019; Grote 2009). Concepts, theories, methods and tools and case studies would be worth reviewing through climate change lenses to appreciate what is valid, what is actionable as such, what needs adaptation, and what would better be dropped.

Among the contributions in this volume, Weyer (2024) explores the added value for policymakers of a simulation tool which could "anticipate" the impact of certain decisions, considering distinct behaviors for different social groups and integrating possible nonlinearities in collective reactions.

9.3.4 Questioning the Role of Science and Scientists

Despite the urgency of curbing the greenhouse gas emissions pointed out by scientists since the 1970s (see Meadows et al. 1972), the pace of change in practices is still far from what would be needed to meet the challenge. As such, climate change is an obvious illustration that science may not be the best place from which to change society. Inconvenient truths can remain ignored on purpose when there is no easy way to deal with them.

This observation is a reminder of an issue also clearly identified in safety science, where the long-lasting recognition of the limitations of some safety management approaches or safety governance regimes has not led to any evolution outside of academia. The dilemma for safety scientists working in the social or political sciences is still vivid. Should this community become more prescriptive (as engineering disciplines often are), thereby partly contradicting some of its findings to make things happen?

More inclusive approaches such as that suggested by Bleicher (2024) could be a way for researchers to be more influential or at least engage in a discussion with public decision-makers and representatives of civil society.

9.4 Conclusion

The discussions held during the workshop as well as the previous chapters of this book allowed for identifying mutual impacts of climate change and safety both in theory and practice. Concepts such as uncertainty, risk, accident or disaster are used in both domains, but a closer look at what they encompass leads to highlighting nuances that do not seem to be commonly acknowledged or addressed. Some existing theories and methods could be adapted to address safety in a climate change era, and new lenses might be needed to revisit basic assumptions taken for granted as to the context in which safety is and will be managed. At the same time, the significant research work done in safety management on complexity, uncertainty, disasters and resilience can be a useful base to support reflections on how to live with climate change.

At a more societal level, the interplay of safety and climate change induces new dilemmas in terms of expectations and acceptability. The current governance regimes working in silos and involving distinct actors are challenged. How the dilemmas are currently addressed at different managerial and institutional levels needs further investigation. Some promising approaches suggesting new modes of governance are being experimented, but are still at the stage of research initiatives today.

Finally, this new climate change landscape and the urgency for action poses again with even greater urgency the question of the role of scientists and their influence on society, a question that safety management researchers, especially those coming from the social sciences, have been struggling with for decades.

Articulating safety and climate change raises a wide range of issues in many areas. Although very few are new taken individually, what might be more unprecedented is the obvious entanglement between them.

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