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Alicia Gutting, Per Högselius, Teva Meyer & Melanie Mbah *

Abstract: *»Geographien der Kernenergie. Eine Einführung«.* Nuclear energy has long attracted the attention of scholars in the humanities and social sciences. With this HSR Special Issue, we would like to push the scholarly frontier by highlighting the geographies of nuclear energy in the past and present. Nuclear energy is inherently interwoven with geography. We argue that to fully appreciate and grasp nuclear energy's geographical and spatial dimensions, approaches from a range of disciplinary and interdisciplinary fields are needed. This special issue thus includes contributions from history, geography, political science, technology assessment, science and technology studies (STS), and other fields. This article introduces this topic by outlining the state of the art of the geographies of nuclear energy and discusses different conceptual frameworks of how to understand nuclear-space interactions. In addition, the individual articles in this issue are briefly presented here and discussed within the research context. The articles themselves cover the geography of nuclear energy from beginning to end: from the mining of uranium, the planning and construction of nuclear power plants, the formation of public resistance, and the cooling of nuclear energy sites as well as the evolution of research centres and, last but not least, the political control and storage of nuclear waste. The collection of articles published here were part of the double session "Geographies of Nuclear Energy," presented at the RGS-IBG Annual International Conference 2021, and of the session "Atomic Rivers," presented at the ESEH Conference 2023.

Keywords: Nuclear geography, nuclear power, radioactive waste, nuclear disposal, infrastructure, spatiality, nuclear siting, uranium.

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1. Introduction

The history of nuclear energy can be traced back to the 1890s, when Henri Bequerel and Marie and Pierre Curie began to explore the phenomenon of radioactivity. This was followed during the first decades of the 20th century by several key discoveries in physics and chemistry, the interpretations of which led to new theorizations of the atom and its nucleus. By early 1939, German and Austrian scholars were able to experimentally demonstrate and interpret the phenomenon of nuclear fission, that is, the splitting of heavy atomic nuclei. Researchers from different countries contributed to advancing the scientific frontier. But after the outbreak of World War II, much of the transnational exchange of knowledge ceased, as nuclear research came to be regarded as strategically important. What up until then had been essentially a scientific endeavour now switched to practically oriented experimental activities, centred on the efforts to build an atomic bomb (Radkau 1981; Rhodes 1986).

After the war and the violent destruction of Hiroshima and Nagasaki, civilian nuclear technology developed as a spinoff from work on nuclear weapons. The period from 1950 to 1965 became a dynamic time of experimentation, leading to the development of numerous reactor types for electricity production, most of which were inspired by military experience (Mazuzan and Walker 1984; Hill 2013; Schmid 2015). Based on the light water reactor, which ultimately emerged as the dominant reactor technology in most nuclearizing countries, civil nuclear power then saw its commercial breakthrough. It paved the way for what can be described as the "golden age" of nuclear power, which lasted from the mid-1960s to the mid-1980s. Virtually all nuclear power plants in operation today around the world were built during that period, with the exception of a few countries – mainly South Korea and China – whose expansion in the field came later. However, if we look at statistical data on the world's nuclear power plants, we see how the number of new construction starts already began to fall in 1976 (IAEA 2023). Scholars have offered different interpretations of this reversal, citing internal technical problems in making the nuclear power plants work as intended, stricter requirements from regulatory authorities, growing public criticism against nuclear power, and weaker growth in demand for electricity throughout the industrialized world following the energy crises of the 1970s (Radkau 1983; Kaijser, Meyer, and Rubio-Varas 2021; Wellock 2021).

The stagnation in nuclear power expansion was reinforced in the 1980s and 1990s by the Three Mile Island accident (1979), the Chernobyl disaster (1986), and later by the Fukushima catastrophe (2011). If we look specifically at the European atomic age, we see that nuclear power's contribution to energy supply grew rapidly and sometimes at an exponential rate over a period of 25

years. Towards the end of the 1980s, no fewer than 182 commercial nuclear reactors were in operation throughout Europe. In the 1990s, however, the tide turned. Almost no new reactors were added, while a growing number of nuclear power plants were shut down. European nuclear power thus ended up in a phase of stagnation and decommissioning, which we are still in today. Currently, approximately one third of the former 182 European reactors have been shut down, and the number of operational reactors continues to decrease year by year (IAEA 2023).[1]

Intriguingly, this distinctly negative trend co-exists with a recent wave of expectations, in many countries, for a "nuclear renaissance." Among other things, from around 2020, alongside the interest in standard large-scale nuclear power plants, the world has seen a surge of interest in "small modular reactors" (SMRs) which, or so the advocates claim, are cheaper, safer, and more flexible than the large reactors built during the "golden age" (Lehtonen 2021; Kojo et al. 2023). Nuclear energy is portrayed by its proponents as being critically important for scaling up electricity supply, for combatting climate change and urban air pollution, and, in the world's democratic countries, for reducing energy dependence on Russia and other unfriendly nations. Governments in countries such as France and Sweden actively seek to promote a new wave of nuclear construction. Yet nuclear energy remains as controversial as ever in its social, political, and economic context. Opposition to nuclear energy continues to loom large in Germany and other countries. Critics point to the atom as a risky, dangerous, and unnecessary technology with unsolved – or even unsolvable – problems concerning spent nuclear fuel and radioactive waste. Economists emphasize the extreme cost escalations of building new nuclear power plants. Recent nuclear projects such as Olkiluoto in Finland, Flamanville in France, and Vogtle in the United States rank high in the list of the world's most expensive buildings. That is a far cry from earlier visions of nuclear energy "too cheap to meter" (Strauss 1954). Proponents of renewable energy sources, meanwhile, view nuclear energy as a hopelessly inflexible energy source that cannot match the intermittent nature of solar and wind power. At the same time, nuclear energy is seen as competing with renewable energy projects, potentially channelling investments away from the latter.

Given these radically different views on nuclear energy's future, now is a good moment for historians and social scientists to revisit the past and present of the atom's societal career. In this HSR Special Issue, we propose to do this by taking a step back from the better-known social and political conflicts around nuclear energy and "star accidents" such as Chernobyl and Fukushima. Instead, we choose to approach nuclear's conflictual past and present from a geographical perspective. This, we believe, has the potential to both

[1] These figures include all current EU member states plus Britain and Switzerland.

add an important dimension to the academic discourse on nuclear energy and enrich the public and political debate.

2. Geographies of Nuclear Energy: The State of the Art

Place and its significance for humans has long been a matter of interest for scholars from multiple disciplines. In this section, we take a closer look at the extent to which place and space play a role in historical and social studies of nuclear energy.

2.1 The Spatial Dimension in Earlier Nuclear-Historical Research

Nuclear energy has long captured the imagination of historians. However, while they have excelled in highlighting the complexity of *temporalities* in nuclear developments, historians have only to a limited extent scrutinized the *spatialities* of such developments. Many of the best-known studies in the field are surprisingly non-spatial in character, taking the form of national histories that gravitate around reactor choices and political rivalry with foreign designs (Radkau 1983; Anshelm 2000; Michelsen and Särkikoski 2007; Hecht 2009; Sovacool and Valentine 2012; Hill 2013; Hristov 2014; Schmid 2015; Bini and Londero 2017; Rubio-Varas and de la Torre 2017). The "star" theme is the American light-water reactor technology's contested rise to global dominance. Nuclear historians tend to be more fascinated by a few key *personalities* – such as Enrico Fermi and Robert Oppenheimer (Rhodes 1986), John Cockcroft (Hill 2013), Werner Heisenberg and Otto Hahn (Carson 2010), Niels Bohr (Knudsen et al. 2012), and Igor Kurchatov, Nikolai Dollezhal, and Anatoly Alexandrov (Schmid 2015) – than by the key *sites* of nuclear developments. Recent initiatives such as the HSR Focus on "Global Protest against Nuclear Power,"[2] which examined anti-nuclear activities at several interconnected geographical scales (Mignon Kirchhof and Meyer 2014), along with a number of intriguing site-specific histories (Kupper 2003; Hecht 2009; Brown 2013; Guth 2022; Frey 2019; Storm, Krohn Andersson, and Rindzevičiūtė 2019; Sesma-Martín 2020) have taken steps in this direction, but much remains to be done.

Some of the most promising attempts to bring the spatial dimension into nuclear-historical research come from environmental historians, in particular in their studies of how radioactive particles migrate through nature, eventually ending up in human bodies. Notable recent works on this theme include Robert Jacobs' *Nuclear Bodies* (2022), which traces the global victims both of nuclear weapons testing and civilian atomic accidents, and Togzhan Kassenova's *Atomic Steppe* (2022), which tells the story of the rise and fall of

[2] https://www.gesis.org/en/hsr/full-text-archive/2014/391-cultural-life-scripts (Accessed January 12, 2024).

Kazakhstan as the key site for Soviet nuclear weapons testing and its consequences for the country. Kate Brown's innovative book *Plutopia* (2013) traces the intertwined US and Soviet plutonium disasters, and her *Manual for Survival* (2019) looks into the shocking health and environmental effects of the Chernobyl disaster. The theme of radiation's impact on human health is also omnipresent in Gabrielle Hecht's (2012) seminal work on the history of uranium mining in Africa, which likewise entails a strong spatial dimension. Several other works trace the health and environmental consequences of radioactive contamination in the US West following uranium mining, plutonium production, and nuclear weapons testing (Ringholz 1989; Amundson 2002; Findlay and Hevly 2011; Mogren 2002; Pasternak 2010; Voyles 2015; Weisiger 2012). Davide Orsini, meanwhile, in *The Nuclear Archipelago* (2022), which is set in the Mediterranean, has explored how fears of radioactive contamination take material form through the construction of sociotechnical systems for the radiological monitoring of the environment.

Historians have sought to come to grips with the spatial dimension of nuclear energy in a few additional ways. Sara Pritchard's *Confluence* (2011) explores France's nuclear history through the lens of the remaking of the Rhône River during the 19th and 20th centuries. Pritchard shows that the construction of numerous nuclear facilities contributed to the reengineering of the river as a geographical entity. By extension, she demonstrates that nuclear energy can be integrated into longer histories of efforts to "improve" nature. A related, though more succinct narrative is offered by Richard White in *The Organic Machine* (1995), which integrates the history of the plutonium-producing reactors at Hanford, Washington, into an eco-biography of the Columbia River basin. Authors such as Jacob Darwin Hamblin (2021), Helene Anne Curry (2014), and Stefan Guth (2022) further discuss the spatial dimension in their elaboration of historical visions to put nuclear energy to work for agricultural development. In another work, Hamblin (2009) analyses the history of techno-scientific debates and policies to dump radioactive waste in the oceans. Other examples of spatial-environmental explorations of nuclear energy in historical perspectives include Dorothy Nelkin's (1971), Robert Durant's (1984), and Samuel Walker's (1989) early studies of thermal pollution from US nuclear power plants.

Recent years have also seen a growing interest from historians to explore nuclear disasters, which in at least a few cases brings the spatial perspective to the forefront (Walker 2009; Plokhy 2022) – a trend that is also reflected in popular culture through the success of Johan Renck's HBO miniseries *Chernobyl* and the Netflix documentary *Meltdown: Three Mile Island*.[3] Another intriguing subfield that has seen a marked upswing is the study of nuclear energy from a heritage point of view, which has intersected in interesting ways

[3] Renck's *Chernobyl* inspired a recent scholarly discussion featuring several shorter articles published in Technology & Culture. See, in particular, Rindzevičiūtė (2020) and Schmid (2020).

with research on nuclear waste management (Kasperski 2018; Rindzevičiūtė 2021; Storm, Krohn Andersson, and Rindzevičiūtė 2019; Bauer and Penter 2022). Philosophers and anthropologists, for their parts, have sought to come to grips with nuclear memories and the confusing time dimensions in nuclear waste management, introducing notions such as "memory sites" (Ialenti 2020; Knowles 2022; Wendland 2020; Kalmbach 2013).

2.2 "Nuclear" in Geography

The development of nuclear technologies for power generation, weapons manufacturing, food conservation, and medical procedures have multiplied the places intertwined by this industry. In geographical research, this spatial deployment is described as a planetary unifying force having "irrevocably merged radiation with land and bodies" due to its "capacity to connect disparate geographies through its vibrant and invisible materiality" (Alexis-Martin and Davies 2017). Yet, the atomic complex produced an archipelago of places which are unevenly nuclear. Mobilizing the concepts of "geography of sacrifice" (Lerner 2012; Cram 2016a) and "nuclear colonialism" (Endres 2009; Nelta 2011; Jacobs 2013), research documented how unequally the burden of its environmental and social consequences was spatially shared. From an ontological perspective, Gabrielle Hecht's already mentioned work (2012) on uranium mining in Africa showed that the very act of categorizing and considering places as nuclear was a technopolitical process fluctuating through time and space, changing among actors, and decoupled from the actual nature of the activity. While names like Hiroshima, Chernobyl, or Fukushima became "geosymbols" (Bonnemaison 1981) of the atomic complex, other spaces should gain this nuclear association as well because "nuclear technology also inhabits more mundane spaces" (Alexis-Martin and Davies 2017), such as hospitals using nuclear medicine daily and food-packing facilities ionizing fruit and vegetables. The various components of this atomic archipelago are not evenly considered as nuclear, and neither do places which once hosted atomic activities lose their nuclearity after decommissioning.

While scholars took interest in the spatial dynamics of the atomic complex early in the 1950s, nuclear geography experienced a renewal in the 2010s following the multiplication of radioactive waste disposal projects and the 2011 Fukushima accident (Alexis-Martin and Davies 2017). Once lacking integration and coherence, this constellation of research led to growing theorization efforts (Alexis-Martin et al. 2021). Yet, a by-product of this renewal is the inflation of geographical concepts applied to signify places of the atomic complex: "atomic lands" (Osseo-Asare 2016), "nuclear oasis" (Kari 2010), "nuclear community" (Hänninen and Yli-Kauhaluoma 2014), "nuclear territory" (Storm 2020), "nuclear landscapes" (Pitkanen and Farish 2018), "nuclear spaces" (Stanley 2013), and "nuclear zones" (Alexis-Martin and Davies 2017).

These concepts do not constitute a coherent corpus. Articles do not always formulate definitions for the terms they employ and often switch from one to another without indicating any clear differences between them. Furthermore, while these notions have their own epistemology in geography literature, papers rarely reflect their ontologies.

Nuclear spaces are distinguished by the presence of *things* related to the atomic complex. Some articles describe them as places enduring demographic and socioeconomic transformation caused by industry (Karafantis 2014). Others tend to focus on the presence of radiation and radionuclides. Being invisible and intangible, the active process of designating radiation is what allows "nuclear places to come into being" (Alexis-Martin and Davies 2017). Nuclear spaces – eventually coined as "irradiated spaces" (Alexis-Martin and Davies 2017) – are distinguished here both by the existence of radiation and by the human actions of measuring, controlling, and delineating, sometimes by means of maps or warning signs (Luedee 2021). Finally, nuclear spaces are places of exception "where different rules, modes of behaviour and exclusions apply" (Davies 2015), delimited by negotiated boundaries.

Consistent with a Sackian epistemology (Murphy 2012), *nuclear territories* are defined by the borders that delimit them. For Storm (2020), *nuclear territories* are "social and industrial enclaves" whose borders are required by "the level of secrecy and levels of calculated risk." Their very existence is linked to the presence of nuclear activity. Osseo-Asare (2016) is the only scholar mobilizing the concept of *atomic land*, which he occasionally switches for "nuclear territory" and "toxic territory." Borders define *atomic lands*, assembled through administrative categorization and judicial work to enclose spaces dedicated to nuclear operations.

Recurrently employed in papers on Chernobyl or Fukushima, *nuclear zones* refer to well-delimited areas purposely produced to protect society from risks, be it from radiation (Alexis-Martin and Davies 2017; Lerner 2012b; Overy 2020) or atomic weapons in the case of *nuclear-free zones* (Clements 2015). Again, *zones* are defined by what they enclose and by the peculiar norms, rules, and laws which are applied.

Nuclear landscapes gained the greatest momentum in the literature, emboldened both by the renewal of landscape research (Benediktsson 2007) and by its association with other concepts such as "landscapes of justice" (Pitkanen and Farish 2018), "landscapes of threat" (Davies and Polese 2015), "anti-therapeutic landscapes" (Davies 2015), "post-industrial landscapes" (Dawney 2019), "subterranean landscapes" (Saraç-Lesavre 2019), and "irradiated landscapes" (Masco 2004). The *nuclear landscape approach* differs from the previous border-centred one.[4] The term "landscape" is used to signify the fluidity of radiation, indicating "that these spaces are ultimately impossible to

[4] A number of articles also use "nuclear landscapes" in research on the issue of dark tourism in post-accidental or post-industrial zones (Rush-Cooper 2020).

enclose" (Pitkanen and Farish 2018), blurring the "boundary between contaminated and safe" (Davies and Polese 2015). Intangible and uncontainable (Masco 2004), "radiation could be anywhere, yet appears nowhere: it resides in everyday spaces and on ordinary objects" (Pitkanen 2017), thus turning nuclear landscapes into places of uncertainty (Pitkanen 2020). This concept is nurtured by the dualism between visibility and invisibility at the core of research on landscapes (Figueroa 2018). This invisibility goes beyond the imperceptibility of radiation. Nuclear landscapes are outlined both by the "physical scars" (Wills 2001) and by the everyday actions (Pitkanen 2017), political acts (Pitkanen 2020; Wills 2001), and ideologies (Dawney 2019; Edwards 2011; Runyan 2018; Saraç-Lesavre 2019; Stanley 2008) sustaining them.

Nuclear communities have been mobilized in research investigating the acceptance of radioactive waste projects. While mainly an actor-centred and relational concept, it bears two competing significations. On the one side, *nuclear communities* are municipalities hosting nuclear facilities (Haraldsen 2014; Litmanen, Kojo, and Kari 2010) coalesced by a "nuclear identity" (Kojo, Kari, and Litmanen 2012). Sometimes coined as "nuclear neighbourhood" or "host communities" (Kojo, Kari, and Litmanen 2012; Litmanen, Kojo, and Kari 2010), they are characterized by their dependency shared with the industry, which sustains unbalanced power relations. Congruent with this approach, (Blowers, Lowry, and Solomon 1991; Blowers 1999) introduced the notion of *nuclear oasis* to distinguish remote, economically marginal, and powerless communities, which are more prone to accept nuclear activities. On the other hand, *nuclear community* refers to the results of strategic tools used by the nuclear sector to build acceptant collectives around its facilities. Nuclear communities are seen "not only as residents but also as a socially constructed imagery of togetherness associated with nuclear works, local culture, and the past" (Hänninen and Yli-Kauhaluoma 2014).

Table 1 The Different Geographical Concepts of Nuclear-Space Interactions

Concept	Defining ideas	References
Nuclear spaces	Places enduring socioeconomic transformations induced by the industry	(Karafantis 2014; Meyer 2014, 2021)
	Designation of radiation in space by human actions	(Alexis-Martin and Davies 2017; Luedee 2021)
	Exception; different rules and behaviour; exclusions	(Alexis-Martin 2019; Cram 2016b; Davies 2015)
Nuclear territories	Bordered and delimited space; enclaves for nuclear activity; protection; secrecy and risk	(Broderick 2016; Carpenter 2012; Davies 2013; Storm 2020)
Atomic lands	Bordered and delimited space through administrative and judicial work	(Osseo-Asare 2016)
Nuclear zones	Well-delimited areas; human-produced; protecting society from risk; peculiar norms and rules	(Alexis-Martin and Davies 2017; Blowers 1999; Clements 2015; Lerner 2012b; Overy 2020)
Nuclear landscapes	Fluidity; impossibility to enclose; intangibility; visibility vs. invisibility; imperceptibility of radiation; produced by everyday actions and ideology; materiality vs. immateriality	(Davies and Polese 2015; Dawney 2019; Edwards 2011; Figueroa 2018; Kaur 2021; Masco 2004; Pitkanen 2017, 2020; Pitkanen and Farish 2018; Runyan 2018; Rush-Cooper 2020; Saraç-Lesavre 2019; Stanley 2008; Stawkowski 2016; Wills 2001)
	Evolution of countries' nuclear policies	(Bradford 2012)
Nuclear communities	Municipality hosting nuclear facilities being economically and politically interrelated with the industry; actor-centred	(Haraldsen 2014; Kojo, Kari, and Litmanen 2012; Litmanen, Kojo, and Kari 2010; Litmanen et al. 2017; Vilhunen et al. 2019)
	Acceptant community of actors built by nuclear industries around facilities; actor-centred	(Hänninen and Yli-Kauhaluoma 2014)
Nuclear oasis	Remote, peripheral, economically marginal and more prone to accept nuclear activities	(Blowers 1999; Blowers, Lowry, and Solomon 1991; Kari 2010)

2.3 Governing Nuclear Geographies

In the political sciences, nuclear energy gained importance in connection with the rise of anti-nuclear movements. The significance of the geographical dimension, in this research, came to the fore especially in the debate about the disposal of nuclear waste. Scholars observed how anti-nuclear movements stimulated public awareness that "something is going wrong" in the course of nuclear weapon testing, dumping nuclear waste in the sea, serious nuclear accidents, and the realization that even civilian use of nuclear energy

might be a threat to human health. Meanwhile the nuclear industries needed to find spatial solutions for their waste – for low- and medium-level, but especially for high-level waste (mainly spent nuclear fuel). To this end, political actors and the nuclear industry tried to enforce solutions by seeking sites for nuclear waste disposal following a classical "decide-announce-defend" approach to decision-making, without participatory procedures. This happened, for example, in France, Switzerland, Germany, and the United States – and in all of these countries, the attempts failed (Di Nucci, Brunnengräber and Isidoro Losada 2017; Hocke and Kallenbach 2015; Krütli et al. 2010; Macfarlane and Ewing 2006). These difficulties in announcing a site for radioactive waste disposal generated an interest in alternative ways of managing the waste issue in its spatial context, from government in terms of a top-down decision-making to governance, as a process of decision-making in which a broader range of actors are integrated (Chhotray and Stoker 2009; Kuppler and Hocke 2019).

In the scholarly community, there has been considerable interest in how and why countries differ in their political approaches. The literature on nuclear waste governance has been addressing such differences in descriptive ways for years. Studies focused primarily on describing the changes from a government approach to more participative governance approaches in countries such as France, Belgium, and Germany (Hocke and Kallenbach 2015; Parotte and Delvenne 2015; Lehtonen 2010). Analysts have emphasized that there are significant differences between the countries examined, which can be traced back to historical and socio-cultural variations as well as to existing political traditions and frameworks. In France, for example, attitudes towards nuclear energy are much more positive and the overall role of nuclear energy in the economy much more significant than in Germany (Meyer 2018). In geographical terms, the centralist character of the French state still has its effects today, which means that the regional administrative structures can act independently only to a limited extent, with the consequence that decisions at the regional level on certain topics (e.g., transport) differ from those at the national level (Sperfeld et al., n.d.). In contrast, the political life of nuclear power in Germany is characterized by numerous controversies and conflicts, which have their roots in the nuclear-critical attitude of the population. At the same time, federalism in Germany is very pronounced. This affects the search for a site for a high-level waste repository and makes a national consensus difficult or puts a process in the foreground that is based on the criteria of participation, science, learning, self-questioning, and transparency (Hocke and Brunnengräber 2019). Therefore, the political science literature focuses primarily on nuclear waste governance, rooted in historical experiences of former muddling-through and decide-announce-defend politics with a future orientation, in order to find procedural elements for decision-making as the basis for a participative and fair governance that is oriented

towards the common good and has a long-term perspective to guarantee generational fairness and sustainability.

3. The Diversity of Nuclear Geographies: An Overview of the Special Issue

The articles in this special issue encompass different segments of what the nuclear industry refers to as the nuclear fuel cycle. The "cycle" concept may be criticized (Hill and Ashipala 2024, in this special issue), because it is hard to find any truly "cyclic" features of nuclear energy in its global setting. Apart from a limited amount of spent nuclear fuel that has undergone "reprocessing," the popular vision of a nuclear circular economy, much promoted in nuclear energy's early days, has not materialized. This is, of course, the underlying reason why the quest for a final repository for spent nuclear fuel, as discussed in the preceding section, has become so prominent in the political debate. Rather than using the cycle concept, it would seem more reasonable to use the notion of a nuclear fuel supply chain, where the fuel moves from the mine to various processing and reactor sites and ultimately ends up in waste repositories. Such chains highlight the intricate spatial-systemic interconnectedness of what at first glance may seem like isolated nuclear activities, and they remind us that nuclear energy is not only about nuclear power plants. As emphasized in some of the best-known works on nuclear history (Hecht 2012; Brown 2013), it is useful and necessary for historians and social scientists to explore uranium mining and milling, uranium conversion and enrichment, spent nuclear fuel reprocessing, and radioactive waste management. Not to be forgotten are the often-controversial transports of uranium, nuclear fuel, and radioactive waste and the extensive research and development (R&D) complexes that mushroomed across the world during and after World War II. Our special issue highlights this diversity of nuclear activities, offering in-depth analyses not only of nuclear power plants in their historical-geographical context, but also of the uranium mining industry, the global uranium trade, research activities, and waste management.

The first two articles in the special issue analyse geographies of uranium. *Christopher R. Hill and Saima Nakuti Ashipala* zoom in on Namibia's Rössing uranium mine, the world's largest until 1984. This mine became controversial over the years as Namibia was controlled by Apartheid South Africa from the onset of the atomic age until the country's independence in 1991. Tying into Gabrielle Hecht's theorization of "nuclearity" as a socially constructed feature of uranium that is transformed as the ore, in raw and refined forms, moves from one place to another, Hill and Ashipala discuss how Rio Tinto Zinc, the multinational company that brought the Rössing mine into production, was

able to keep it up and running even in the face of international sanctions launched in the 1980s. They argue that we can only explain the conflicts that loomed large at that time by adopting a longer historical perspective, while including both "vertical" and "horizontal" geographies in the analysis. In particular, uranium mining in Namibia, as well as at many other sites worldwide, can be seen to build on historical forms of resource colonialism. The Rössing mine's success, after it started up in 1976, was rooted in a socio-ecological reordering of the territory that German colonists and scientists had initiated nearly a century earlier. Hill and Ashipala show that it is no coincidence that Germany, Britain, and South Africa – the three countries that colonized Namibia at different moments in history – also became the ones most deeply engaged with uranium mined at Rössing during the 1970s and 1980s. Moreover, they trace the parallel emergence and evolution of Rio Tinto as an increasingly global actor after its founding in 1874. In the post-war era, its managing directors firmly believed that "multinationals should fill in the void left by British decolonisation," a perspective that came to shape the company's rise to dominance at Rössing and, more widely, in global uranium mining.

Michiel Bron, in his contribution to the special issue, adds to the historical-geographical analysis of uranium mining by analysing the interconnections between the oil and uranium industries and the development of a uranium cartel. He shows that there has been a long history of entanglement between oil and uranium extraction, originating in shared geological resources and spillovers of technological know-how. His analysis focuses particularly on one of the major companies in uranium mining, Gulf Oil, which participated in the uranium cartel. He identifies two technology spillovers that served to bridge the gap between oil and uranium exploration. The first, radioactive well logging, made it possible to locate new oil reservoirs. When it was used for uranium mining, it helped to identify uranium deposits in different geological structures. Bron shows how this invention can be traced back to the activities of geologists and geophysicists as well as to innovations of oil exploration companies in various countries, such as Germany, France, and Russia. After World War II, the US Atomic Energy Commission (AEC) took interest in this technology as a promising method for locating uranium deposits. The AEC installed an advisory board of leading oil actors and opened the uranium market to private actors, promising to buy all uranium found. At the same time, other countries began to engage in uranium mining, for example, the Netherlands and France, in their colonial territories. In this context, new inventions, such as in-situ leaching (ISL), were devised, which stimulated oil companies to engage in uranium mining. ISL is the second technology at focus in Bron's analysis of the entanglements between oil and uranium. ISL dissolves the minerals with chemicals and pumps the solution up to the ground surface. This made uranium mining much cheaper, as excavation in underground or open pit mines was no longer needed. These innovative

developments led to price decreases on the uranium market, which explains why the uranium cartel – which was dominated by five big companies based in different countries – was implemented, and why Gulf Oil became part of it.

Next, *Matteo Gerlini's* article shifts the focus away from uranium mining and towards the geographies of nuclear research and development. More precisely, Gerlini spotlights the tensions between European identity, the Italian region of Lombardy, and the Centre Commun de Recherche (Euratom's Joint Research Centre, CCR/JRC) that was established at Ispra in the years around 1960. In doing so, Gerlini illuminates an early nuclear discourse in relation to geography. In these early days of nuclear energy research, debates often concerned the location of research centres, similar to the construction of nuclear power plants but with a different focus. Gerlini traces how negotiations took place within the Euratom Commission and which locations were considered suitable. For in addition to the European plans, the individual countries also had their own plans, which they prioritized. This case also stands for an early example of European integration because the employees of Ispra saw themselves neither as members of the local population nor as belonging to Euratom. The newcomers were given the opportunity to leave their mark on the place, as it was, like so many places of nuclear energy, rather rural. These "development attempts" were not always well received and led to controversies. Nevertheless, a certain enthusiasm can be noted among the Ispra employees, who also perceived their new place of residence as an opportunity for lasting Europeanisation.

The next four articles in the special issue explore the geographies of commercial nuclear power plants. *Alicia Gutting and Per Högselius* examine nuclear development from a riverine perspective, focusing on the Rhine, the Danube, and the Elbe. They note that nuclear power development has traditionally been researched mainly from a national perspective. By taking river basins as their main unit of analysis, the authors challenge the national focus and introduce a transnational research angle. Taking inspiration from earlier social and historical research on rivers, Gutting and Högselius conceptualize cooperation and conflict around nuclear power in the three river basins by distinguishing between three dimensions of "water interaction": space, environment, and infrastructure. By applying the water interaction concept, the authors highlight that conflict and cooperation often go hand in hand and cannot be analysed apart from each other. By also including the tributaries in their analysis, the authors are able to trace how intensively nuclear planning was pushed along the individual rivers. Not all planned nuclear power plants were completed, but the maps show how immense the planning of industry and politics was. Conflicts and cooperation arose in many respects. On the one hand, nuclear energy planners cooperated with non-nuclear actors by making use of and adapting existing water infrastructure in the form of dams

or straightened rivers that ensured a constant flow of cooling water. On the other hand, the rivers as key sources of cooling water for the nuclear plants often generated conflict. For example, nuclear power plants were sometimes planned too close to each other along one and the same river, and concerns were also raised over thermal pollution. Furthermore, the authors show that some nuclear power plants were prevented because they were planned along rivers that also functioned as borders between countries. All in all, the authors provide a comprehensive synthetic account of nuclear planning in (transboundary) river basins and the challenges planners faced from the 1950s on.

Christian Götter, in his contribution, follows up on the nuclear cooling problem by zooming in on three large-scale nuclear projects in Europe: The Oldbury-on-Severn nuclear plant in the United Kingdom and Germany's Biblis in Hesse and Lingen in Lower Saxony. Götter explains how the utilities in charge of these projects sought to make sure that sufficient volumes of cooling water would always be available to cool the reactors. In the process, surrounding nature, notably in the form of rivers, became part of wider envirotechnical systems centring on the nuclear plants. The arrangements differed strongly from site to site. At Oldbury, the main envirotechnical component was a cooling pond built in a tidal river. At Biblis, the focus was on multiple cooling towers. And at Lingen, the engineers relied on an artificial lake, supported by tall dikes, in combination with a single, massive cooling tower. The article explores how these arrangements led to local controversies, which typically dominated the public discourse about nuclear energy in the local setting. However, Götter also shows that the controversies could often be overcome, especially if the cooling systems were equipped with features that were regarded as positive for the surrounding environment and social life.

The river perspective is also strongly present in *Louis Fagon's* contribution. On the basis of historical maps from French archives, Fagon reconstructs how French decision-makers continuously constructed and developed different kinds of risk zones around the two nuclear power plants of Superphénix and Saint Alban on the Rhône from the 1970s to the 1990s. Despite the fact that the potential risk posed by nuclear power plants was very difficult to conceptualize geographically, planners and officials set up multiple zones around each plant. Fagon distinguishes between five types of zones, ranging from "the area affected by the risk," "the area involved in the decision-making process," "the zone receiving information," "the economic benefit zone," and "the area of contestation." While the existence of zones around nuclear power plants is a well-known phenomenon, Fagon uniquely demonstrates how they emerged and evolved historically. He also shows which actors were involved in zoning around nuclear power plants. While the zones were initially defined by the French electricity company, EdF (now EDF), other actors were able to negotiate new zones through social pressure. Fagon argues that it remains

questionable to what extent risks such as radioactivity or the thermal load of the Rhône can be zoned and where risk begins and ends. Zones around nuclear power plants also meant that communities near nuclear power plants had a right to monetary compensation or could demand taxes and more information. In the course of the 1980s, "local information commissions" were established, which kept the local population informed about risks and developments around nuclear power plants, while also highlighting the fact that the risks emanating from nuclear power plants cannot actually be limited geographically.

Jan-Henrik Meyer's article adopts a strongly transnational approach to nuclear geographies, Meyer bridges border studies with European integration history, analysing the ultimately failed attempts to establish common European regulations for siting nuclear facilities in border regions. As theorized by geographers, borders often constitute valuable resources. This is why, Meyer argues, nuclear power plants are often located near borders. There, nuclear builders were able, or so they hoped, to access cooling water from border rivers, share construction costs with neighbours, or externalize ecological and political impacts. Growing awareness of the cross-border environmental impact of nuclear installations led to increasing transnational tensions. Using both EU and national archives, Meyer points to two Christian Democratic actors, Belgian Prime Minister Leo Tindemans and German member of the European Parliament Hanna Walz, as the main proponents of a common European siting policy for nuclear installations. But despite being addressed as early as Euratom's foundation in 1957, this issue was never fully regulated by the European Commission. This failure, as Meyer explains, can be interpreted through different lenses. From the perspective of European integration, it reflects the difficulties introduced by the unanimity rules in EU decision-making. Defence of national interest, particularly by France or Western Germany, favoured bilateral negotiations over European procedures, while small countries, such as Ireland, pushed in the opposite direction. Geographical imaginaries played a central part in discussions over siting policies. For France, the lack of domestic coal resources and its situation upstream of major rivers suitable for nuclear power plants encouraged Paris to disavow any European-scale solution. Incapacity to regulate cross-border installations at the European level is also a consequence of the waning interest in this issue during the 1970s, as declining growth rates following the energy crisis decelerated the construction of new nuclear power plants on the continent. However, as Meyer concludes, this failure was not complete. European countries continuously pursued bilateral consultation when nuclear infrastructure was to be located at borders, and these experiences paved the way for international interventions on cross-border issues by the International Atomic Energy Agency following the 1986 Chernobyl accident.

The last two articles in the special issue explore geographies of nuclear waste. *Melanie Mbah and Sophie Kuppler,* in their article, look at the long-term problem of ensuring safety of nuclear waste storage. The authors argue that people's relations to (their) place need to be considered in the decision-making for a storage or reprocessing site. Siting processes are usually rather controversial, as nobody wants nuclear waste in their vicinity. Mbah and Kuppler note that while the concept of place attachment has been applied in various disciplines before, it has not been researched in relation to nuclear power. The authors argue that insights into place attachment can be used for successful decision-making concerning the siting of nuclear waste as locals apply different boundaries to "their" place than, for example, municipal borders. In that way locals could be involved in the decision-making process, which would lead to a higher rate of acceptability of nuclear waste sites. Focusing on three specific locations – Recklinghausen, Görlitz, and Heilbronn – the authors show that the sense of belonging to a place can be essential for the local population. The sense of belonging varies depending on the region, but the results clearly show that the consideration of the sense of place should be an important factor in the long-term planning and governance of the storage of nuclear waste. The local population must be given the chance to accept the final repository and integrate it into their sense of belonging. The last thing such a place needs is insecurity and unrest due to hurt feelings.

Teva Meyer's contribution, finally, offers to continue the conceptualization effort of the spatial dimensions of Gabrielle Hecht's "nuclearity" by studying it through the frame of "bordering." Both concepts focus on the creation of socio-spatial distinctions, built upon strategies of ordering and othering spaces. The article's central attention is directed to analysing when spaces come to be treated as nuclear. To do so, Meyer studies frontier objects which navigate between the *nuclear* and *non-nuclear* world. He focuses on very low-level radioactive wastes in Germany and their process of clearance, which refers to the administrative act of denuclearizing radioactive materials and allowing them to be recycled or disposed of in the conventional sector. The emphasis is on studying the movement of these materials and identifying how their circulation tends to nuclearize some places and not others. Meyer argues that the nuclearity of space is dependent on three main dynamics. First, nuclearity appears in situations of negotiations and tensions between actors where the nature of space is debated. Space is labelled as nuclear when such discourses are dominant and others silenced. Second, nuclearity is revealed in practices and performances. These entail the everyday actions of militants who perform the division of space between ordinary and abnormal, conventional and nuclear, by treating them as distinct from others through differentiated policies. Here, Meyer's article highlights the importance of sticking to nuclear *mundanity* as compared to nuclear *exceptionalism* to understand its everyday consequences. Third, nuclearity is multidimensional, as factors

constituting it are contingent on actors evolving in particular historical and geographical contexts. Finally, Meyer underlines the role of *agency*, of local actors and militants perceiving political opportunities in nuclearizing one place, depending on their own strategic agendas.

4. Concluding Thoughts

With this special issue we want to push the scholarly frontier of nuclear-historical research by merging it, in an interdisciplinary way, with social science research on nuclear energy. We want to let historians interact with geographers, political scientists, STS scholars, and others around one of the most intriguing themes in the past and present of nuclear energy: the theme of geography and space. The nine articles in the special issue demonstrate the surprising richness of this theme, and how it can lead us to new insights that help shape not only discourses about the past, but about the present and the future as well. The articles enrich the field by theorizing the geographies of nuclear energy in terms of zones and territories, nuclearity and bordering, vertical and horizontal geographies, resource colonialism and water interaction, nuclear settlers and place attachment, among other concepts that the authors mobilize. They also span a vast empirical domain, comprising studies of different parts of the nuclear fuel cycle – from uranium mining and nuclear research and development to large-scale nuclear power plants and radioactive waste management – while targeting both a number of European regions and wider global developments. It is our hope that this variety of theoretical and empirical lenses, and our effort to let different approaches speak to each other, will serve as inspiration for further research.

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