

Same events, different trajectories: why countries reacted differently to the oil crisis, Chernobyl and Fukushima

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ABSTRACT

Nuclear energy is a low-carbon technology playing a critical role in present and future energy systems. Yet, historically, national nuclear systems have followed strikingly divergent paths (some expanding and consolidating, while others phasing out) despite facing similar events, such as oil crises or nuclear accidents, occurring abroad. Understanding the reasons behind these divergent paths is an empirically relevant and academically underexplored area of research. This paper addresses this gap by investigating the factors that shape the resilience and continuity of national nuclear large technological systems (LTSs) (i.e., complex socio-technical configurations comprising both physical and non-material elements), analysing four European LTSs: France, the UK, Germany, and Italy. Through a multiple-case study approach, this paper examines how socio-economic, political, technological, socio-cultural, and environmental factors have shaped national responses to three key exogenous events, i.e., the 1970s oil crisis and the Chernobyl and Fukushima nuclear accidents. The analysis reveals that the pre-event configuration of factors within each nuclear LTS plays a critical role in shaping its post-event trajectory. While France and the UK maintained and reinforced their nuclear systems, Germany and Italy experienced destabilization and phase-out. This study presents a novel framework for understanding nuclear LTS resilience based on the dynamic alignment of key factors empirically identified in the four countries' LTS. Our results have broader implications for understanding the necessary interventions in a nuclear LTS to increase its resilience by investigating and assessing the configuration of factors and their evolution.

1. Introduction

The global energy landscape is currently undergoing a profound transformation, driven by the dual imperatives of mitigating climate change and ensuring a secure and resilient energy supply (Kanger and Schot, 2019; Markard et al., 2012; Sovacool et al., 2023). In this context, nuclear technology is strategic (Markard et al., 2020; Mathew, 2022), offering large-scale, reliable, and low-carbon electricity generation (Knapp and Pevec, 2018; Liu et al., 2023; Teshome, 2023). Yet, the history of nuclear power reveals striking cross-national divergence. Countries with similar levels of technological development, economic capacity, and geopolitical challenges have taken fundamentally different paths in their nuclear energy policies. Some have expanded their nuclear fleets and integrated them into long-term energy strategies, while others have halted development or opted for a complete phase-out. France and Italy, two European democracies with comparable access to natural resources, economies and human development, are

clear examples. This extreme variability in the development of nuclear power defies deterministic assumptions about technological diffusion and stresses the importance of national socio-political, institutional, and cultural configurations in shaping nuclear energy trajectories (Jasanoff and Kim, 2009; Wiliarty, 2013).

Deploying nuclear technologies consists of developing Large Technological Systems (LTSs), multifaceted constructs that encompass both tangible assets (e.g., nuclear power plants, fuel facilities, transmission networks) and intangible components (e.g., regulatory frameworks, organizational structures, and stakeholder networks) (Hughes, 1987; Markard and Truffer, 2006). The concept of LTSs goes beyond the single power plant, as they represent “*technological systems that contain messy, complex, problem-solving components [...] both socially constructed and society shaping*” (Bijker et al., 1987, p. 62). LTSs are deeply embedded within broader socio-political contexts, necessitating alignment between technological capabilities, societal needs, and political will to ensure success (Hughes, 1987). According to Hughes (1987), LTSs

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develop following a broadly defined evolutionary pattern with overlapping and backtracking phases: invention, development, innovation, transfer, growth, competition, and consolidation. Covering these phases, the literature on nuclear LTSs spans from the early stages of nuclear physics to the most recent technological innovations (e.g., SMRs, SFRs, and HTGRs) (Duchnowski et al., 2022; Guo et al., 2021; Zeng et al., 2020).

Numerous studies have also explored the barriers and enablers influencing the growth, competition, and consolidation of nuclear LTSs (Adamantides and Kessides, 2009; Jewell, 2011; Jewell and Ates, 2015; Neumann et al., 2020; Sovacool and Valentine, 2010). Yet, according to Hughes (1987), the evolution of LTSs does not stop after the consolidation phase, as LTSs also develop a distinctive style shaped by social, economic, and technical factors, defined as “momentum”. The momentum of an LTS represents its resilience and resistance to change, seen as its capacity to maintain directional stability. Investigating the momentum of nuclear LTSs is essential because trajectories of nuclear LTSs have exhibited considerable heterogeneity across nations (Sovacool and Valentine, 2012; Wiliarty, 2013). For instance, France has developed and consolidated a robust nuclear LTS, largely driven by strong governmental support, long-term strategic planning, and a centralized energy policy (Hecht, 1998). In contrast, Italy’s nuclear ambitions were cancelled following public opposition and a referendum in 1987 and 2011, leading to the complete phase-out of its nuclear infrastructure despite initial investments in reactor development and construction (Franchino, 2014). So, the key question is the following: why do national nuclear LTSs undertake different trajectories?

We approach this question as industrial engineers with extensive experience in the nuclear sector from a management and policy perspective, which makes us particularly attentive to how LTSs evolve across different national contexts but within an increasingly interconnected global energy landscape. Against this background, this paper investigates the factors that shape the resilience and continuity (i.e., momentum) of nuclear LTSs by adopting a multiple-case study approach and considering the evolution of nuclear LTSs in the UK, France, Germany and Italy. These countries have historically invested in and deployed nuclear technologies. However, nuclear LTSs have taken different trajectories over the last few decades, with France and the UK currently maintaining an active reactor fleet, while Italy and Germany have phased out nuclear power.

2. Literature review

2.1. Large technological systems (LTSs)

The concept of LTS originates from the work of Hughes (1983), who developed a framework for analyzing sociotechnical transformations. LTSs encompass both a methodological approach for examining large-scale infrastructure and production systems and a category of complex, interdependent phenomena that benefit from an LTS lens (Van Der Vleuten, 2009). Hughes (1987, p. 62) defines LTSs as “*technological systems that contain messy, complex, problem-solving components*” and that are both socially constructed and society-shaping. Similarly, Joerges, (1989, p. 24) describes them as “*complex and heterogeneous systems of physical structure and complex machinery*” materially integrated over space and time. LTSs are not solely physical; they also incorporate non-material elements such as regulations, norms, and institutional actors, including utility providers and investors (Markard and Truffer, 2006).

A key example of an LTS is the electricity supply system, which consists of interconnected actors, institutions, and technical components, including power producers, trading companies, grid operators, regulators, and technical standards (Markard and Truffer, 2006). These elements function in an interdependent network that ensures system stability while embedding electricity supply in a broader sociotechnical environment. LTSs are inherently socio-technical (Mondschein et al.,

2021), meaning they are composed of physical artifacts (e.g., turbines, power lines), organizational entities (e.g., utility companies, financial institutions), scientific components (e.g., research, university programs), and legislative frameworks (e.g., regulatory laws) (Hughes, 1987). Integrating these elements is essential for the system’s operation, as any alteration in one component affects the entire network (Hughes, 1983). This dynamic interaction underscores the concept of “*enmeshment*”, wherein technological, social, and institutional factors are interwoven to sustain the system’s functionality. While often adapted into structured analytical models in later studies to operationalize the concept of LTS, these elements should be understood as flexible conceptual guides to help illuminate salient patterns and relationships in complex developments (Hughes, 1983). As such, their use benefits from balancing analytical structure with an awareness of the interpretive flexibility inherent in the original formulation, enabling the framework to remain responsive to diverse historical and contextual settings.

The development of LTSs follows a loosely structured life cycle consisting of overlapping phases (Hughes, 1987). Initially, the “*Invention*” phase introduces a radical technological innovation, which is then refined during the “*Development*” phase through testing and adaptation to economic and social conditions. The “*Innovation*” phase sees the integration of manufacturing and commercial components, enabling the system’s market expansion. The “*Technology Transfer*” phase involves adapting the system to new contexts, often presenting significant challenges due to site-specific design constraints. As the system gains acceptance, it enters the “*Growth*”, “*Competition*”, and “*Consolidation*” phases, competing with alternative technologies. Over time, systems acquire “*Momentum*”, which gives them the appearance of autonomy, although they remain influenced by external factors (Hughes, 1987). Some scholars (Markard et al., 2020; Sovacool et al., 2018) have also introduced a “*Stagnation*” or “*Decline*” phase, recognizing that systems may eventually lose viability or be replaced. All these phases are not strictly linear, as they overlap, backtrack, and interact dynamically throughout an LTS’s evolution (Hughes, 1987).

LTSs are also networked, meaning they do not function in isolation but are embedded in broader infrastructures and institutional frameworks (Mondschein et al., 2021). Their interdependence implies that changes in one system can influence others, affecting growth trajectories, resilience, and legitimacy (Markard and Truffer, 2006). This characteristic highlights the mutual shaping of technological and social systems, where innovations both reflect and drive societal transformations. Jasanoff (2004) emphasizes this co-production dynamic, wherein technological advancements shape social structures while social changes, in turn, influence technological development. Thus, LTSs have to be understood as evolving, interconnected entities integrating technological, economic, regulatory, and cultural dimensions into a cohesive yet dynamic framework.

2.2. LTS’s momentum

The concept of momentum is a fundamental and intrinsic property of LTSs. “*Momentum is the end stage in which technical systems have become embedded in society, resulting in many linkages between firms, regulatory bodies, departments in educational institutions, and research laboratories.*” (Geels, 2007, p. 124). When an LTS acquires momentum, it displays directional stability and a growth rate suggesting high velocity. These properties are not autonomous but result from alignments between social and technical elements. The concept of momentum describes the “*apparent autonomy of large complex technological systems, resisting pressures for change*” (Van Der Vleuten, 2009). The physics metaphor suggests the existence of a “*mass*” (in relation to interdependent technical and non-technical elements, including invested capital, actor commitment, employment, user habits, and so forth) traversing a specific “*speed*” within a “*direction*” (such as geographical expansion or scale increase) (Van Der Vleuten, 2009). As Hughes (1983) notes, this “*mass*” consists of machines, devices, structures, and other physical artifacts in

which considerable capital has been invested, as well as the involvement of skilled personnel and the participation of organizations such as businesses, government agencies, professional societies, and educational institutions, all of which add to momentum. While momentum is not exclusive to LTSs, as smaller or non-systemic technologies may also exhibit it, the scale and complexity of LTSs often lead to particularly pronounced forms of momentum.

Indeed, mature LTSs, characterized by significant momentum, exhibit strong resistance to change (Van Der Vleuten, 2009). In LTSs, this momentum often reaches a greater scale due to their socio-technical complexity and embeddedness, such that “only extreme external conditions like warfare, oil crises, environmentalism, and government interference may change the development trajectory” (Van Der Vleuten, 2009, p. 221). However, investigating the destabilization of an LTS, Summerton (1994) identifies five key factors that facilitate the “opening up of systems,” reducing their resistance to change. These include: i) internal system problems and how actors perceive them, ii) external risks such as safety or environmental concerns, often expressed through consumer pressure, public protests, and regulatory interventions, iii) shifts in competitive conditions that prompt system builders to adapt their strategies, iv) political events or broader contingencies, including war or its threat, and v) changes in cultural values and dominant political ideologies (Geels, 2007). Furthermore, alterations in the external circumstances of an LTS significantly influence changes within the systems themselves (Summerton, 1994).

2.3. Nuclear LTSs

The literature investigating the momentum of nuclear LTSs is scarce. Yet, key determinants identified in investigating the early phases of the LTS's development also significantly impact the subsequent phases. The development of nuclear LTSs is, in fact, influenced by a complex interplay of enablers and barriers. These determinants stem from broader energy policy dynamics and additional structural conditions identified in the literature. By analyzing these factors, it is possible to understand the forces that promote or hinder the integration of nuclear LTSs into national energy systems. We will then compare these enablers and barriers from the literature with empirical observations to understand whether they also constitute key factors in determining the momentum of nuclear LTSs.

2.3.1. Enablers of nuclear LTS

State Guidance and Centralized Policy - A critical factor in the development of nuclear LTSs is state intervention. Given the “socio-technically inflexible” nature of nuclear power (Rochlin, 1995), centralized planning facilitates effective coordination across supply chains and regulatory frameworks (Brutschin et al., 2021; Neumann et al., 2020). State involvement, either directly through government actions or indirectly via state-owned utilities, is crucial for managing nuclear energy projects, which require extensive oversight and high degrees of coordination (Sovacool and Valentine, 2010). The political structure of a state also plays a role in the adoption of nuclear LTS. Centralized governments, such as in France, are effective at overcoming public opposition and implementing nuclear policies compared to decentralized systems like the USA (Brutschin et al., 2021). Additionally, governments often employ strategies that link nuclear power with national technological progress, thereby fostering public acceptance of its associated risks (Neumann et al., 2020; Valentine and Sovacool, 2010). Lastly, studies remain inconclusive on whether democracy accelerates or impedes nuclear energy expansion (Csereklyei et al., 2016; Thurner et al., 2014).

Energy Security - Energy security is a fundamental driver of nuclear LTS adoption. The ability to generate power domestically reduces reliance on energy imports, making nuclear technology particularly attractive for countries with a significant dependency on foreign energy sources (Adamantiades and Kessides, 2009; Brutschin et al., 2021).

Uranium, unlike fossil fuels, is easy to store and does not degrade over time, further enhancing nuclear energy's appeal (Lidsky and Miller, 2020). The expansion of nuclear LTSs has also been linked to the growth in electricity demand. In Japan, for example, rapid industrial expansion in the 1990s necessitated secure and large-scale electricity generation, prompting further development of nuclear LTSs (Cherp et al., 2017a; Markard et al., 2020). However, the extent to which energy security concerns directly translate into nuclear LTS expansion remains debated in the literature.

Public Support and Low Civic Activism - Public attitudes towards nuclear power significantly impact its adoption. Countries with high nuclear dependency tend to experience lower levels of public opposition, as citizens fear the economic repercussions of abandoning their nuclear infrastructure (O'neil, 1999). Conversely, nations with strong anti-nuclear movements often face delays or cancellations of nuclear projects (Neumann et al., 2020). Political and institutional contexts also shape civic activism, influencing the intensity of opposition to nuclear technology (Kitschelt, 1986).

Industrial Supply Chain - A well-developed industrial supply chain is crucial for the sustainability of nuclear LTS. The nuclear sector demands specialized skills, advanced engineering capabilities, and stringent safety protocols, necessitating a highly trained workforce (Stirling and Johnstone, 2018). Industry consolidation in recent decades has streamlined operations, ensuring compliance with safety standards while enhancing efficiency (Adamantiades and Kessides, 2009). Countries with robust nuclear industries, such as the USA and France, benefit from strong supply chain infrastructures that support continued investment and development.

Technocratic Influence and Political Authority - A policymaking approach dominated by technical expertise can facilitate nuclear expansion by minimizing political and public debate (Sovacool and Valentine, 2010; Valentine and Sovacool, 2010). Governments that prioritize expert-driven decision-making over democratic deliberation often encounter fewer obstacles in implementing nuclear policies (Neumann et al., 2020).

Climate Change and International Cooperation - The role of nuclear energy in reducing greenhouse gas emissions has strengthened its position as a sustainable energy source (Stern, 2007). The climate crisis, along with volatile fossil fuel markets and geopolitical instability, has accelerated efforts across countries, particularly in the Global North, to decarbonize electricity systems, electrify end-use sectors, and redesign the infrastructures of energy provision (Hille, 2023; Parias et al., 2025). In this context, nuclear power has re-emerged as a prominent, albeit controversial, actor in the debate on energy transition (IPCC, 2022; Markard et al., 2020). International cooperation has also been instrumental in nuclear LTS diffusion, with established nuclear states assisting newcomers in developing their programs (Jewell and Ates, 2015). For example, France has shared its nuclear expertise with various countries, thereby facilitating global nuclear expansion (Price, 1993). Additionally, geopolitical alliances have historically influenced nuclear technology dissemination, particularly during the Cold War, when superpowers provided nuclear assistance to allied nations (Adamantiades and Kessides, 2009).

Military Nuclear Programs - A strong linkage between military and civilian nuclear programs has been a critical enabler for the development and long-term resilience of nuclear LTSs (Stirling and Johnstone, 2018). In countries with a strong nuclear military industry, the pursuit of nuclear application in defense fostered the creation of a powerful, state-controlled technocracy, often insulated from public debate, which could steer the civilian energy program with minimal opposition (Hecht, 1998; Walker, 2000). This dual-use structure fostered a secure industrial supply chain, a highly specialized workforce, and advanced industrial manufacturing capacity, creating technological and institutional lock-in that benefited the civilian sector (Sovacool and Valentine, 2012). Framing nuclear programs as essential for national security further justified massive, long-term public investment and helped marginalize

anti-nuclear sentiment (Meyer, 1995). The overlap between military and civilian infrastructures also facilitated, particularly in the early days, knowledge transfer, secured stable funding, and ensured sustained political commitment, with synergies where the civilian LTS is deeply intertwined with military objectives from its inception (Acosta et al., 2020).

2.3.2. Barriers to nuclear LTS formation

Public Perception and Risk Attitude - Nuclear power faces significant public resistance due to concerns over safety, waste management, and nuclear weapons proliferation (Adamantiades and Kessides, 2009). Events such as Three Mile Island (1979), Chernobyl (1986), and Fukushima (2011) have reinforced negative perceptions, influencing policy decisions worldwide (Fuhrmann, 2012; Gourley and Stulberg, 2013). Challenges about nuclear waste disposal persist as a significant concern for the public. Many countries lack publicly accepted solutions for long-term waste management, which has hindered further nuclear development (Brutschin et al., 2021). Additionally, fears regarding nuclear weapons proliferation further complicate nuclear LTS expansion, necessitating stringent international regulatory frameworks (Adamantiades and Kessides, 2009).

Economic and Financial Constraints - The economic viability of nuclear energy is a relevant issue, particularly in Europe and North America. High capital costs, long construction timelines, and financial risks deter investment (Sovacool et al., 2014). The liberalization of electricity markets has further exacerbated these challenges by reducing government support, thereby limiting nuclear competitiveness in deregulated environments (Brutschin et al., 2021). Market uncertainties and regulatory hurdles have contributed to a decline in nuclear power plant construction, particularly in Western economies.

Competition from Alternative Technologies - Advances in renewable energy have intensified competition within the energy sector. Wind and solar technologies have experienced significant cost reductions, making them, in some contexts, more attractive alternatives to nuclear power (Brutschin et al., 2021). Historically, periods of high oil prices spurred nuclear expansion, but recent technological advancements in renewables have shifted the energy landscape, posing additional challenges for nuclear LTS (Csereklyei et al., 2016; Markard et al., 2020).

3. Methodology

Our research leverages a multiple case study, adhering to the methodological framework established by Yin (2009). By employing a multiple case study approach, we aim to generate compelling and comprehensive empirical evidence, thereby enhancing the robustness of our study (Brookes et al., 2015) and providing a broader foundation for analytical generalization.

3.1. Research setting

The empirical context of this multiple case study encompasses the nuclear LTSs of Germany, Italy, the UK, and France. These countries were selected due to (A) their historical investment in nuclear technologies for electricity generation, and (B) being broadly comparable in terms of geographical location (Europe) and socio-economic and demographic indicators. Also, crucially, these countries have been purposively selected considering that despite their initial establishment of nuclear LTSs in all four nations, their respective trajectories have diverged significantly over the past decades. While France and the UK maintain active reactor fleets, Italy and Germany have opted to phase out. Italy abandoned its nuclear program shortly after its inception, with nuclear energy peaking at only 4,6 % of total electricity production in 1989 before a complete phase-out (IAEA, 2023). In contrast, France has pursued an extensive nuclear strategy, with nuclear power currently accounting for about 65 % of its electricity supply (WNA, 2025), positioning it as a central pillar of the national energy system. Germany and

the UK occupy intermediary positions between these extremes. Germany, akin to Italy, phased out its nuclear LTS after decades of debate, shutting down the last reactors in 2023, though nuclear power had previously contributed up to 30 % of its electricity production (WNA, 2024a). Conversely, the UK keeps nuclear energy as a core component of a diversified energy portfolio, contributing approximately 15 % of the country's electricity generation (IEA, 2024).

This sample provides a robust foundation for comparative analysis, as each country's distinct trajectory in nuclear LTSs exemplifies the diverse outcomes that can emerge from different LTSs characteristics and resilience.

3.2. Data collection, data analysis and validation

During data collection, we adhered to the three principles outlined by Yin (2009). We triangulated the data by utilizing multiple sources of information, including scientific literature, institutional webpages, newspapers, and reports, and cross-checked and validated it from different perspectives. This approach involved creating a case study database and maintaining a chain of evidence to enhance the reliability of our findings. The data collection followed a theoretical saturation approach (Eisenhardt, 1989), characterized by continuous sampling until no new relevant data emerged. A total of 266 documents were collected and analyzed for this purpose (Table 1).

Our research began by analyzing peer-reviewed scientific literature to establish a credible and rigorous foundation (Bell, E., Bryman, A., & Harley, B., 2019). Subsequently, we examined governmental reports, institutional web pages, and sources from educational institutions, consulting firms, political parties, government bodies, and international organizations. Additionally, we analyzed the websites of companies involved in nuclear LTSs and news outlets. This comprehensive data collection strategy ensured that our study captured contemporary discussions, public perceptions, and evolving narratives surrounding nuclear LTSs.

We conducted an abductive qualitative thematic analysis based on secondary qualitative data to derive the factors that shaped the development and resilience of nuclear LTSs (Thompson, 2022). Following Braun and Clarke (2006) six-step approach (i.e., data familiarization, generating initial codes, searching for themes across the data, reviewing themes, defining themes, and producing the report) we integrated these steps with the creation of a codebook as suggested by Thompson (2022). We used the software "Atlas.ti" to facilitate the coding process (Sadraei et al., 2023). We followed the System of Provision approach theoretical framework (Dei et al., 2025; Fine and Leopold, 1993) to conduct the thematic analysis. Such an approach allows a nuanced and systemic understanding of the nuclear LTSs dynamic evolution by comprehensively mapping the involved agents, the key relations and structures, the ongoing processes and the material culture of nuclear power (Bayliss and Fine, 2020). The thematic analysis resulted in the identification of 60 codes grouped into 8 themes (See Annexes).

The results of the thematic analysis were subsequently refined and validated through two workshops involving experts in nuclear LTSs. Specifically, the first workshop, held online in February 2024, lasted 3 h and involved 12 experts in nuclear LTSs from six European countries. The second workshop, conducted in person in September 2024, lasted 8 h and included 18 experts from eight European countries. The primary

Table 1

List of documents analyzed for each country.

	Italy	Germany	UK	France
Scientific Literature	21	32	30	22
Institutional Web Pages	13	15	16	18
Online Newspapers	21	16	13	13
Reports	4	11	16	5
Total	59	74	75	58

purpose of the workshops was to refine and validate the key factors identified and presented in Section “Key Factors in Nuclear LTSs’ Momentum”.

4. Historical evolution of nuclear LTSs

4.1. The German nuclear LTS

The development of the nuclear LTS in Germany was initially driven by aspirations of national prestige (Tompkins, 2021) and technological advancement (Renn and Marshall, 2016). As detailed by Augustine (2018), these ambitions were closely tied to the emergence of a technocratic vision of nuclear power in post-war West Germany, where political and industrial elites saw nuclear technology as both a symbol of modernity and a pathway to reassert national scientific authority. In its formative years, particularly until the late 1950s, the German nuclear LTS was also shaped by strategic and defense-oriented ambitions. Although post-war restrictions formally prohibited military nuclear development, political and industrial elites explored avenues to retain technological competencies that could serve both civilian and potential future military applications (Radkau, 1983).

However, economic concerns regarding its viability and the substantial initial investments required led to skepticism among energy companies (Hake et al., 2015), necessitating significant governmental subsidies to facilitate adoption (McCauley et al., 2018; Schreurs, 2012). Governmental support during this early phase was motivated by energy policy objectives and broader geopolitical considerations, as West Germany sought to re-establish itself as a technologically advanced and strategically significant actor within the Western bloc during the Cold War (Radkau, 1983).

The emergence of anti-nuclear protests in the 1970s, catalyzed by the 1979 Three Mile Island accident (Hake et al., 2015), evolved into a consolidated movement in the 1980s, further strengthened by the 1986 Chernobyl disaster (Ionescu, 2012). These incidents profoundly influenced public sentiment against the nuclear LTS (Arlt and Wolling, 2016; Hake et al., 2015; McCauley et al., 2018; Renn and Marshall, 2016), making Germany one of the most staunchly anti-nuclear nations (Schreurs, 2012). This opposition was significantly shaped by political actors’ and newspapers’ narratives (Kepplinger, 1988).

The Green Party, which emerged from the anti-nuclear movements of the 1980s, leveraged environmental concerns to gain parliamentary representation following Chernobyl (Ionescu, 2012; Renn and Marshall, 2016). The party formed part of a broader political and institutional network that influenced nuclear policy, wherein multiple government levels and stakeholder interests, spanning civil society, industry, and political agendas, complicated decision-making (McCauley et al., 2018). This complex interplay enabled the anti-nuclear movement to exert sustained pressure on public discourse and policy formulation (McCauley et al., 2018; Renn and Marshall, 2016).

In parallel with the rise of anti-nuclear movements, the German nuclear industry undertook significant public relations and lobbying campaigns during the late 1980s and 1990s in an attempt to counter growing skepticism and rebuild societal trust following the Chernobyl (1986) disaster. As Brunig (2025) details, these efforts combined strategic communication initiatives, engagement with policymakers, and the promotion of nuclear safety narratives, seeking to reframe nuclear energy as a reliable and secure component of the national energy mix. While these campaigns achieved partial success in sustaining political debate, they were ultimately insufficient to reverse the broader cultural and political shift against nuclear power, which continued to gain momentum into the early 2000s.

This long-standing opposition culminated in a landmark policy decision. In 2002, the Social Democratic-Green coalition government under Chancellor Schröder passed a fundamental amendment to the Atomic Energy Act. This legislation effectively sealed the country’s first nuclear phase-out (the Atomausstieg). It established a legal framework

that prohibited the construction of new nuclear power plants, banned the reprocessing of nuclear fuel from 2005 onwards, and limited the operational lifetimes of the existing reactor fleet. This decision marked a critical turning point, institutionalizing the decline of the German nuclear LTS and severely weakening its political and industrial momentum. In Germany’s political discourse, nuclear power was increasingly framed not as a climate protection technology but as a competitor to renewables, a stance that reinforced its marginalization even in the context of growing climate concerns (Friederich and Boudry, 2022).

This structural weakness is essential to understanding the events that followed. While a subsequent conservative government under Chancellor Merkel briefly reversed course in 2010 by extending the lifetimes of some reactors, this decision proved politically fragile. As shown in comparative analyses of post-Fukushima policy-making in Germany and Japan, the German reversal was shaped by a unique combination of pre-existing phase-out legislation, strong anti-nuclear sentiment, and the political salience of nuclear risk (Nam et al., 2021). The Fukushima disaster in 2011 acted as a powerful catalyst that triggered a rapid and definitive political U-turn (Nam et al., 2021). Facing immense public pressure and fearing electoral repercussions, Merkel’s government not only reversed the 2010 extension but legislated an accelerated phase-out, cementing the trajectory established in 2002. Germany’s nuclear policy has been highly responsive to shifts in public opinion (Arlt and Wolling, 2016; Renn and Marshall, 2016) and has often prioritized political imperatives over purely economic or industrial considerations (Skea et al., 2013; SPIEGEL International, 2011). The response of Christian Democrat leaders following Fukushima exemplifies this dynamic: viewing nuclear energy as a political liability, they feared electoral repercussions and the potential loss of coalition opportunities with the anti-nuclear Green Party, leading to their rapid endorsement of a nuclear phase-out (Skea et al., 2013; SPIEGEL International, 2011).

The media further reinforced anti-nuclear sentiment, particularly in times of crisis, by serving as the primary source of information and shaping public discourse (Arlt and Wolling, 2016). Media coverage following major nuclear accidents has historically catalyzed national debates on nuclear LTS, further intensifying public opposition (Hake et al., 2015; Wiertz et al., 2023). This opposition was also indirectly rooted in early Cold War politics, when the blurred boundaries between military and civilian nuclear ambitions contributed to public mistrust of the industry, a sentiment that persisted long after military considerations ceased to influence nuclear policy (Radkau, 1983).

4.2. The UK nuclear LTS

The development of the nuclear LTS in the UK was initially driven by military needs, specifically plutonium production, with the first large-scale nuclear plant established at Calder Hall in 1956 (Teräsväinen et al., 2011). This strategic focus shaped early reactor designs, prioritizing military objectives over electricity generation (Hirose and McCauley, 2022). During the 1970s and 1980s, environmental movements actively opposed nuclear power, particularly in response to the Three Mile Island and Chernobyl (Spence et al., 2010). However, over time, climate change emerged as a more pressing issue, shifting environmental discourse away from nuclear opposition. Prominent environmental figures, such as James Lovelock, have even advocated for nuclear power as a solution to climate change (Corner et al., 2011). Major environmental NGOs, including Greenpeace and Friends of the Earth, have largely ceased significant anti-nuclear campaigns, reflecting a broader public disengagement from nuclear debates (Baker, 2023; Thomas, 2016). As Thomas (2016) notes, the British public exhibits a striking lack of interest in nuclear energy decisions.

This decline in public opposition, coupled with the increasing salience of climate change, has contributed to a gradual acceptance of nuclear technology (Corner et al., 2011). Two key factors underpinned

this shift. First, the media narrative has played a crucial role in shaping public perception. The nuclear industry strategically capitalized on climate concerns, launching a comprehensive media campaign in 2003 to reframe nuclear power as a green energy alternative (Rogers-Hayden et al., 2011). The industry engaged influential media directors, political advisers, and public affairs firms to shift public opinion in favor of nuclear energy (Rogers-Hayden et al., 2011). Second, government rhetoric has actively reinforced this pro-nuclear narrative. Political actors have consistently framed nuclear power as indispensable for energy security, economic stability, and climate change mitigation (Spence et al., 2010). Former Energy and Climate Secretary Ed Miliband underscored this stance, stating, “As a country, we need nuclear [...]. They are necessary for secure supply, tackling climate change, and for the future of our economy” (Mulholland and Teather, 2009, p. 2).

Institutional structures have further shielded nuclear power from widespread political contestation. As Irwin et al. (2000) argued, the nuclear LTS in the UK is embedded within a robust institutional framework of social and technological practices, restricting the scope of public debate. This institutional entrenchment has allowed successive governments to sustain their commitment to nuclear energy despite economic challenges and shifting political landscapes (Irwin et al., 2000).

Economic concerns have remained a persistent issue, particularly in the early 2000s. In 2002, the privatized British Energy faced a severe financial crisis, necessitating government intervention to safeguard energy security and manage nuclear waste (Doyle, 2011; National Nuclear Laboratory, 2016; Rutledge, 2007). The government effectively re-nationalized British Energy, with the bailout costing taxpayers over £10 billion, underscoring the limitations of a free-market approach to nuclear energy (Baker, 2023; Rutledge, 2007; Thomas, 2010). Despite long-standing concerns regarding the financial sustainability of nuclear projects (Thomas, 2016), nuclear power has rarely been a politically divisive issue in the UK. The two major political parties (Labour and Conservative) have historically supported nuclear energy, with no significant ideological opposition (Thomas, 2016). As Baker (2023) notes, political enthusiasm for nuclear LTSs has persisted across multiple governments, leading to continued investment in new capacity.

Although the government initially pledged not to subsidize the nuclear industry, this stance was ultimately reversed due to the necessity of ensuring continued investment in the sector (Connor, 2012; Hendry, 2010; UK Parliament Post, 2022). Despite significant public opposition, the government maintained its commitment to nuclear LTS, reinforcing its perception of the industry as an essential pillar of the UK’s energy strategy. More recently, workforce constraints have emerged as a critical challenge for the UK’s nuclear sector. Government and industry recognize the shortage of skilled nuclear workers as a significant bottleneck (Hoggett, 2014). With a substantial portion of the nuclear workforce nearing retirement, the loss of expertise poses a considerable risk to the timely delivery of new nuclear projects (Hoggett, 2014). These structural challenges further complicate the long-term trajectory of nuclear energy in the UK, despite sustained political and institutional support.

4.3. The Italian nuclear LTS

In the post-World War II era, Italy pursued a strategy of energy diversification, culminating in establishing an ambitious nuclear LTS during the late 1950s and 1960s (IAEA, 2022). By the 1970s, nuclear power was perceived as a crucial solution to energy security, particularly in response to the oil crises of that decade (Walgate, 1979). Beyond its strategic energy role, nuclear technology was also a matter of national prestige, as the Italian government viewed nuclear development as a symbol of international standing (Nucci, 2006). Despite these aspirations, Italy’s nuclear ambitions faced significant obstacles. Chernobyl had a profound impact on global perceptions of nuclear power, exacerbating public opposition in Italy (Contu et al., 2016). This opposition culminated in the 1987 national referendum, which decisively

rejected nuclear energy, effectively dismantling Italy’s nuclear program (Esposito, 2008). Consequently, Italy’s nuclear ambitions remained structurally limited and ultimately unsustainable.

Following the closure of its nuclear plants, Italy faced the complex and costly challenges of reactor decommissioning and radioactive waste management. The safe dismantling of reactors and the disposal of nuclear waste have remained persistent concerns, further exacerbated by ongoing debates over waste facility siting (Morosi, 2016). The financial and technological demands associated with decommissioning have continued to burden public discourse, as radioactive waste management remains unresolved. As Orlando (2019, p.1) highlights, “twenty years after the start of dismantling activities (activities that have already cost 3.8 billion euros, which weigh on the electricity bill), a suitable site has not yet been identified to host the national repository for radioactive waste, as required by safety regulations”.

Although discussions on nuclear energy resurfaced in the early 2000s, primarily driven by the urgency to reduce carbon emissions and mitigate climate change (IAEA, 2022), Fukushima reignited public fears. This renewed apprehension led once again to a public rejection of nuclear power in the already planned second national referendum in June 2011 (Contu et al., 2016). This outcome reinforced the country’s entrenched opposition to nuclear energy, preventing any significant policy shift in its favor.

The media has played a pivotal role in shaping public perceptions of nuclear technology, particularly through its coverage of major nuclear incidents. Media coverage was largely framing nuclear power in a negative light (Contu et al., 2016). This shift in media dynamics further intensified public fears, reinforcing Italy’s long-standing skepticism towards nuclear power. While negative perceptions had already been cemented following Chernobyl, they became even more pronounced in the wake of Fukushima, ultimately solidifying Italy’s anti-nuclear stance.

More recently, however, Italy has seen a political shift toward reconsidering nuclear power. In early 2025, the government adopted an enabling law to develop a new regulatory framework for advanced nuclear technologies, particularly small modular reactors and GenIV reactors, with the aim of reintegrating nuclear energy into the national mix by mid-century (Governo Italiano, 2025). While framed as part of the energy transition and energy security strategy, its implementation remains uncertain, and public opinion continues to reflect the deep-seated skepticism rooted in the 1987 and 2011 referendums (Dei et al., 2026, In Press; SWG, 2023).

4.4. The French nuclear LTS

Following World War II, France initiated its commitment to achieve energy independence, meet rising energy demands (Andersson and Finnegan, 2024; Brouard and Guinaudeau, 2015), and establish itself as a global leader in the peaceful application of nuclear technology, paralleling the military advancements of the USA, Soviet Union, and the UK (Dänzer-Kantof and Torres, 2013).

The success of France’s nuclear LTS has been profoundly shaped by its highly centralized, dirigiste governance model, which has been instrumental in both the establishment and sustained expansion of the country’s nuclear industry (Bertsou and Caramani, 2022; Finnegan et al., 2021). Characterized by an authoritarian decision-making structure, this approach excluded dissenting voices from policy deliberations and fostered the emergence of a powerful technocratic elite, referred to as a “nuclear oligarchy”, that exercised significant control over the country’s nuclear strategy (Sovacool et al., 2019). To further consolidate this control, the government implemented measures designed to insulate nuclear policy from public scrutiny and political contestation (Arnhold, 2022). As Sovacool and Valentine (2010, p. 3805) argue, “the absence of political opposition was supplemented by several government initiatives to insulate the nuclear power development program from public scrutiny to avoid destabilizing public support”. The dirigiste framework thus enabled

the French government to exert substantial influence over economic and energy policies with minimal external interference (Andersson and Finnegan, 2024). This centralized approach proved particularly advantageous during the post-war reconstruction period, facilitating the rapid rebuilding of France's energy infrastructure (Andersson and Finnegan, 2024; Sovacool and Valentine, 2010).

The state's involvement in nuclear energy extended beyond regulatory oversight to direct operational control, largely due to its majority ownership of key nuclear enterprises such as Électricité de France (EDF), Framatome, and Orano (EDF, 2023). This ownership structure granted the government significant leverage over strategic decision-making, ensuring that corporate objectives remained aligned with national energy policy (Andersson and Finnegan, 2024). EDF, in particular, played a critical role in France's nuclear LTS, functioning as both an electricity provider and the primary operator of nuclear power facilities, while also overseeing the contracting and execution of nuclear projects (EDF, 2023). As Andersson and Finnegan (2024, p. 30) observe, EDF's state ownership "provided the conditions for a centralized and technocratic policymaking process that could be controlled from the executive branch".

Furthermore, the government employed a necessitation strategy to frame nuclear technology as indispensable to France's energy security and strategic autonomy (Schweitzer, 2011; Teräsväinen et al., 2011). This narrative was reinforced at the highest political levels, exemplified by former President Nicolas Sarkozy's assertion that "there is not a single serious person who could think that we can meet our objectives with renewable energy sources alone" (Sarkozy, 2010, p. 4). By institutionalizing this perception of dependence on nuclear power, the state cultivated a sense of reliance on its stable electricity supply among the French population (Poumadere et al., 1995). This necessitation strategy also served to marginalize civic opposition, effectively silencing anti-nuclear activism (Arnhold, 2022). As Sovacool and Valentine (2010, p. 3805) argue, "civic activism in opposition to nuclear power development was diluted by the prevalent esprit de corps of volontarisme, which was an emergent penchant on the part of the populace to accept short-term pain for long-term gain". In addition, the pro-nuclear French media played a crucial role in shaping public perception, aligning public discourse with the government's nuclear agenda and reinforcing widespread acquiescence to nuclear energy (Schweitzer, 2011). In recent years, this support has been further cemented by a powerful argument rooted in climate policy: the successful deep decarbonization of the French electricity sector (IEA, 2023). The low carbon footprint of its electricity sector is frequently highlighted as a major national achievement and a competitive advantage within Europe, effectively framing the nuclear LTS as a crucial tool for climate change mitigation. Also, by maintaining strict governmental oversight and strategically controlling public narratives, France has maintained a stable and enduring nuclear energy sector, ensuring its continued dominance within its energy mix.

However, this high degree of interdependence between the state and the nuclear industry has also created significant problems, casting doubt on the long-term sustainability and safety of the French LTS. The centralized, insular nature of this "nuclear oligarchy" has been linked to a culture of poor transparency and a tendency to downplay safety issues. This became evident with the major scandal at Framatome's Le Creusot forge, where manufacturing defects and quality control falsifications in key reactor components were discovered, raising international concern (Schneider et al., 2017). Furthermore, the state-led management culture at major operators like EDF has faced heavy criticism, linked to workplace pressures and a series of employee suicides that mirrored similar crises in other large French state-owned enterprises (Courtet and Gollac, 2020). These issues demonstrate that the same state-centric model that ensured the system's initial growth and stability also fostered deep-seated institutional pathologies.

5. Nuclear LTSs responses to exogenous events

During the evolution of nuclear LTSs in the countries under analysis,

we observed that the main sources of system destabilization stemmed from exogenous events, although such events rarely act in isolation and change can also occur without them. In this study, we consider an "event" as a discrete occurrence that is temporally bounded, widely recognized by relevant actors, and capable of triggering significant reconfigurations in LTSs. This concept draws upon established concepts from diverse fields, including focusing events in policy studies (Birkland, 1997), and landscape shocks in socio-technical transition theory (Geels, 2007), both of which conceptualize events as temporally bounded triggers that may contribute to systemic change. Events in this sense act as external pressures that can reveal, amplify, or accelerate ongoing dynamics by testing a system's momentum (Bijker et al., 1987) and create "windows of opportunity" (or threat) for profound change. Accordingly, we mainly investigate three exogenous events: the 1970s oil crisis, the Chernobyl nuclear accident (1986), and the Fukushima nuclear accident (2011). We selected these events because they mainly occurred outside the national context of the countries examined, they were powerful exogenous shocks directly relevant to the energy and nuclear sectors, their impacts were felt simultaneously across all four case countries, and they are consistently identified in the literature as critical episodes with measurable, system-level effects on nuclear energy policies and trajectories.

5.1. Response to nuclear accidents

The nuclear accidents at Fukushima (2011) and Chernobyl (1986) induced different responses across countries. For instance, the Fukushima incident catalyzed a complete phase-out in Germany, as did the Chernobyl incident in Italy in 1986. In contrast, the UK and France continued to rely on nuclear energy despite the occurrence of nuclear accidents.

Italy and Germany's reactions were mainly driven by public fear (Contu et al., 2016) and media influence (Bohdanowicz et al., 2023; Hake et al., 2015; Perko et al., 2019). In Italy, biased media coverage (Perko et al., 2019), political interference (Esposto, 2008), and limited public awareness of nuclear technology (Nucci, 2006) contributed to distrust and opposition, leading to the phase-out of the four operating nuclear power plants. Public opinion was not uniformly positive (Walgate, 1983), and after Chernobyl, it shifted drastically due to increased fears and anti-nuclear activists' influence (Nucci, 2006). This shift led political leaders to prioritize public sentiment over technical and economic assessments, realigning their positions to maintain electoral support. Initially, however, nuclear energy in Italy benefited from political backing, as the government viewed nuclear energy as a necessity (WNA, 2024b). The media, once technologically neutral, became more critical, further intensifying public concerns (Perko et al., 2019). The combination of shifting public opinion, political realignment, and critical media coverage contributed to the decline in support for nuclear technology. Yet, the Italian nuclear LTS never gained proper momentum, as the system never stabilized and reached only the growth phase.

In contrast to the Italian case, the German nuclear LTS gained momentum and remained stable for several years, despite environmental concerns and protests. However, its long-term trajectory had already been decisively shaped by the 2002 amendment to the Atomic Energy Act under the Social Democratic-Green coalition, which prohibited new plant construction, banned nuclear fuel reprocessing from 2005, and set lifetime limits for the existing fleet (Schreurs, 2012). While a brief reversal in 2010 extended some reactor lifetimes, this decision left the underlying structural weakness of the nuclear LTS unchanged. In this context, the Fukushima nuclear accident (2011) acted as a powerful catalyst that accelerated a phase-out process already legislated in principle (Renn and Marshall, 2016). Germany's swift policy U-turn was facilitated by years of entrenched public skepticism, the institutionalized decline of the nuclear sector, and a political culture in which nuclear energy was framed not as a climate solution but as a competitor to

renewables (Friederich and Boudry, 2022).

Public fear, media influence, and political dynamics played decisive roles (Bohdanowicz et al., 2023; Perko et al., 2019). Opposition dated back to the 1970s, and anti-nuclear sentiment had become a defining feature of German political discourse well before 2011. The Fukushima accident reignited concerns about nuclear safety and raised worries about the potential risks associated with nuclear power plants. In West Germany, media criticism of nuclear power emerged much earlier, gaining traction in the mid-1970s during the society-shaping nuclear controversies and intensifying after the Three Mile Island accident (Kepplinger, 1988). Coverage shifted from a more divided left-liberal-conservative framing to a predominantly critical stance after the Chernobyl disaster (Kepplinger and Lemke, 2014). By the time Fukushima occurred, most German media were already united in their skepticism toward nuclear power, making the Fukushima accident the spark that reignited pre-existing narratives. This long-standing media environment amplified public distrust in the nuclear LTS and shaped the political climate in which Chancellor Merkel's rapid post-Fukushima policy reversal took place (Nam et al., 2021).

The political response in Germany was immediate. In the wake of the Fukushima accident, Chancellor Angela Merkel's government initially announced a temporary shutdown of seven of the country's oldest nuclear reactors, followed by the decision to phase out nuclear energy by 2022 completely (Hake et al., 2015). This accelerated timeline formed part of the broader *Energiewende*, reflecting not only the post-Fukushima shock but also a deeper societal and political alignment toward renewable energy and sustainability that had already eroded the momentum of the nuclear LTS (Hake et al., 2015). This shift was not just a response to the nuclear accident, but also reflected a broader societal and political shift towards renewable energy and sustainability, which had already weakened the nuclear LTS factors configuration.

Conversely, France and the UK were able to maintain their nuclear LTS momentum despite nuclear accidents. In France a centralized governance model, known as *dirigisme*, and a strong government leadership ensured the continuation of nuclear LTS, even after nuclear accidents (Sovacool et al., 2019). The French response to the Chernobyl disaster, for example, also reflected distinctive national discursive strategies. As shown by Kalmbach (2021), official narratives in France downplayed domestic risk, framing the accident primarily as a problem of Soviet mismanagement and technological inferiority. Government statements and much of the mainstream media constructed a geographic and political "otherness" around the disaster, suggesting that such an event could not occur under the highly centralized, technically competent French system. This narrative served a dual function: it reassured the public while reinforcing trust in the state's nuclear institutions. Kalmbach's (2021) comparative analysis of Britain and France reveals that, in both contexts, Chernobyl was less a moment of radical policy shift than a discursive opportunity to reaffirm pre-existing positions, pro-nuclear in France, more ambivalent in the UK, by selectively interpreting the disaster's lessons. In the French case, this selective framing contributed to the stability of the nuclear LTS by maintaining high levels of public acquiescence and shielding nuclear policy from sustained political contestation.

The French government was deeply involved in the interests of the nuclear industry, utilizing its centralized executive authority to direct and regulate the advancement of nuclear energy as a key element of the national agenda (Sovacool and Valentine, 2010). Following nuclear accidents, the government and industry emphasized safety improvements and transparency, with the support of pro-nuclear media, to restore public confidence (Schweitzer, 2011). In the UK, nuclear technology was framed as essential for energy independence (BERR, 2008). The nuclear industry's strategic interests and government leadership remained the primary factors in maintaining nuclear LTSs in both countries, emphasizing the role of governance and media in shaping nuclear policy outcomes (Rogers-Hayden et al., 2011; Thomas, 2016).

We identified two critical differences in how countries managed

nuclear policies in response to nuclear accidents (see Fig. 1). First, the influence of the government and nuclear industry on public opinion and media was a key factor. In both France and the UK, governments successfully reframed nuclear technology to garner public support. France emphasized the importance of safety and energy security (Sovacool et al., 2019), whereas the UK focused on nuclear technology's role in reducing greenhouse gas emissions and achieving climate goals (Doyle, 2011). In both cases, the deployed communication strategy utilized media campaigns and speeches, effectively addressing public concerns and resulting in more robust support for nuclear technology. In contrast, the German government's reframing failed to address widespread environmental concerns effectively, while in Italy, the government prioritized public sentiment. The reframing resulted in a strategy that barely shielded the nuclear LTS from public apprehension toward nuclear technology.

The second significant difference lies in the government structures of the countries. Both Italy and Germany feature elements of direct democracy, which provide citizens with significant "opportunities to make important decisions collectively" (Treccani, 2010, p. 1) and influence nuclear policy decisions. Elements of direct democracy, such as referendums and local veto powers, often resulted in policy decisions driven by public fear and emotion, especially following nuclear accidents (McCauley et al., 2018). Direct democracy can lead to increased politicization regarding nuclear LTS decision-making. Political decisions are made to gain electoral consent rather than based on technical or economic considerations. In Italy and Germany, public involvement has often allowed emotional responses and widespread fear to influence policy decisions, contributing to the eventual phase-out of nuclear LTS in both countries. In contrast, the UK and France operate under a more centralized decision-making structure. The UK direct democracy elements (e.g., referendum) are not as frequent as in Italy, thereby shielding nuclear policies from the volatility of public sentiment. France, although featuring some elements of direct democracy, has managed to control public and private opposition through its centralized dirigiste approach.

5.2. Response to oil crisis

Energy market disruptions, such as the 1970s oil crises and geopolitical conflicts like the Russian-Ukrainian war, have historically destabilized energy supply and pricing, compelling nations to reassess their energy strategies to enhance security and stability (Gajdzik et al., 2024). Such crises expose vulnerabilities in energy systems and necessitate strategic policy shifts. Notably, France's nuclear LTS response to the oil crises of the 1970s diverged significantly from that of Italy, Germany, and the UK.

First of all, variations in national responses to the 1970s oil crises can be attributed to differing levels of energy independence and security concerns, which are recognized as pivotal factors in the rapid deployment of nuclear LTSs' related programs (Jewell, 2011; Jewell and Ates, 2015). However, a deeper analysis reveals that these factors alone are insufficient to explain disparities in nuclear energy adoption. For instance, although France and Italy exhibited similar levels of oil dependency in 1973, at 69% and 75%, respectively (Our World in Data, 2024), France aggressively expanded its nuclear capacity while Italy did not. This discrepancy highlights the importance of additional factors in nuclear long-term sustainability development, even under favorable conditions characterized by energy supply disruptions.

France's success in nuclear LTS expansion can be attributed to its highly centralized governance structure, which enabled swift decision-making and the effective mobilization of resources. The oil crisis served as a catalytic tipping point, reinforcing the effectiveness of centralized authority in garnering public support and accelerating the deployment of nuclear energy infrastructure (Andersson and Finnegan, 2024). Through direct state control over capital allocation, public financing mechanisms, and loan guarantees, the French government

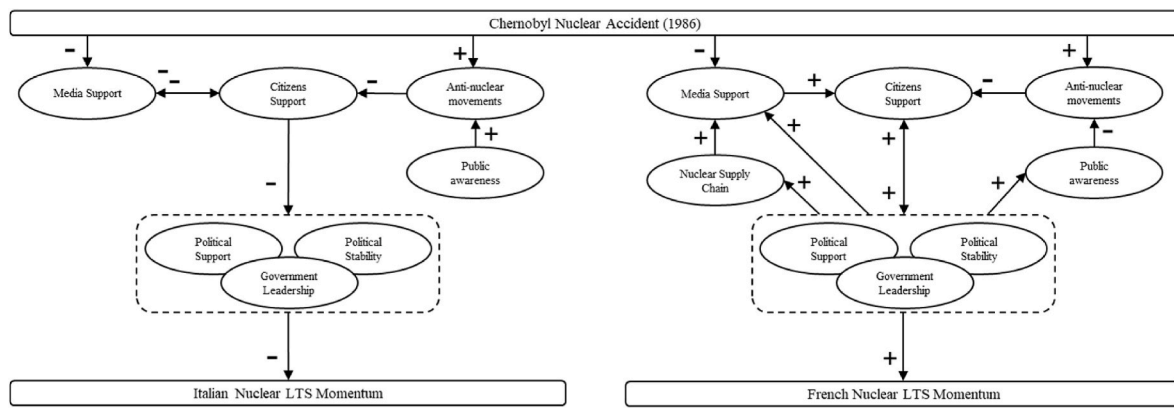


Fig. 1. Polar responses to the Chernobyl nuclear accident.

empowered its state-owned utility, EDF, to rapidly scale nuclear development (Andersson and Finnegan, 2024). In contrast, Italy's fragmented political landscape led to prolonged deliberation and bureaucratic inertia, exposing infrastructural weaknesses and hindering decisive action in response to the crisis (Esposito, 2008).

Moreover, France's pre-existing nuclear infrastructure, encompassing technical expertise, research facilities, and an established industrial base, provided a strong foundation for expansion (Andersson and Finnegan, 2024). Standardizing reactor designs further accelerated deployment by reducing construction costs and mitigating operational risks (Cooney, 2022). Conversely, Italy's comparatively underdeveloped nuclear infrastructure and the absence of long-term strategic planning hindered its capacity to respond effectively. These structural limitations underscore the pivotal role of pre-existing institutional and industrial frameworks in shaping a country's capacity to adopt nuclear energy as a long-term solution.

Furthermore, divergent national perspectives on nuclear energy investment contributed to policy differences. While France and Germany recognized nuclear energy as a viable long-term solution to energy security concerns and invested accordingly, Italy and the UK viewed the protracted development timelines of nuclear projects as a significant drawback. This perception led to relatively lower levels of nuclear investment in these latter countries (Heffron, 2013). Consequently, while France and Germany successfully integrated nuclear energy into their energy mix as a strategic response to external shocks, Italy and the UK remained more reliant on alternative energy sources, limiting their capacity for energy independence and resilience against future disruptions.

The case of France demonstrates that, beyond immediate energy security concerns, factors such as governance structures, public financing mechanisms, infrastructural readiness, and strategic vision play critical roles in shaping national responses to energy crises. These findings suggest that countries aiming to continue and reinforce robust nuclear LTS must not only prioritize energy security but also cultivate institutional and industrial conditions conducive to large-scale nuclear deployment.

While the 1970s oil crises illustrate how external shocks can catalyze long-term strategic shifts in national energy systems, the ongoing energy crisis triggered by Russia's invasion of Ukraine offers a contemporary example of similar dynamics at play, most visibly in Germany. The abrupt reduction in Russian gas imports during 2022–2023, coupled with soaring prices and fears of “deindustrialization,” reignited political and public debates over nuclear power. In response, the Green-Social Democratic-Liberal coalition approved a micro-lifetime extension for three nuclear power plants in stretch-out operation mode, without ordering fresh fuel (Deutscher Bundestag, 2025). A broader nuclear comeback was rejected, a decision that later became the subject of an investigative committee in the Bundestag (Deutscher Bundestag, 2025).

This controversy unfolded against a backdrop of shifting public opinion: polls in 2023 showed growing opposition to the complete phase-out (Tagesschau, 2023), and by 2024–2025, majorities favored a return to nuclear energy (Spiegel, 2024; Stern, 2025). Although these changes have not yet translated into a policy reversal, they suggest that even in countries where the nuclear LTS has been dismantled, severe supply crises can reopen strategic debates and potentially alter long-term trajectories.

5.3. Nuclear LTSs trajectories

Across the four cases, exogenous events acted as catalysts whose effects were mediated by the pre-existing configuration of each nuclear LTS momentum. Consequently, if a negative exogenous event, such as a nuclear accident, occurs at a time when the nuclear LTS is structurally weak or marked by internal tensions, it is more likely that the system's trajectory will be negatively affected. In such a case, the system's internal dynamics will not resist the propagation of the shock but will amplify its effects. Conversely, a nuclear LTS characterized by high momentum will exhibit stronger resistance to change or demonstrate greater resilience. The same logic applies in the case of positive exogenous events. When a solid internal configuration underpins the system, it is more likely to leverage the event as a trigger for a virtuous development cycle. On the other hand, nuclear LTSs with an unfavorable or fragile configuration will fail to capitalize on the opportunity. For this reason, we argue that it is not the event itself that determines the systemic consequences, but rather the extent to which the system's momentum constitutes a fertile or hostile ground for the propagation of its impacts.

We empirically observed that several factors shape the momentum of the LTS, which can positively sustain or negatively affect the nuclear LTS (see section “Key Factors in Nuclear LTSs' Momentum”). These factors, however, are highly dynamic and may undergo reconfiguration in response to external perturbations, such as the aforementioned exogenous events. Fig. 2 illustrates the temporal evolution of installed nuclear power capacity across countries. By marking the time points at which exogenous events occurred, we consider installed capacity as a proxy for the response of the nuclear LTS. It is essential to note that, installed capacity reacts to both positive and negative shocks only with a delay, reflecting the long lead times of planning and construction for expansion and, conversely, the bureaucratic, legislative, and techno-economic constraints that slow down capacity reductions.

6. Key Factors in Nuclear LTSs' momentum

Throughout a nuclear LTS's lifecycle, certain factors assume fundamental importance during specific phases of system evolution (as presented in the “literature review” section). However, some factors,

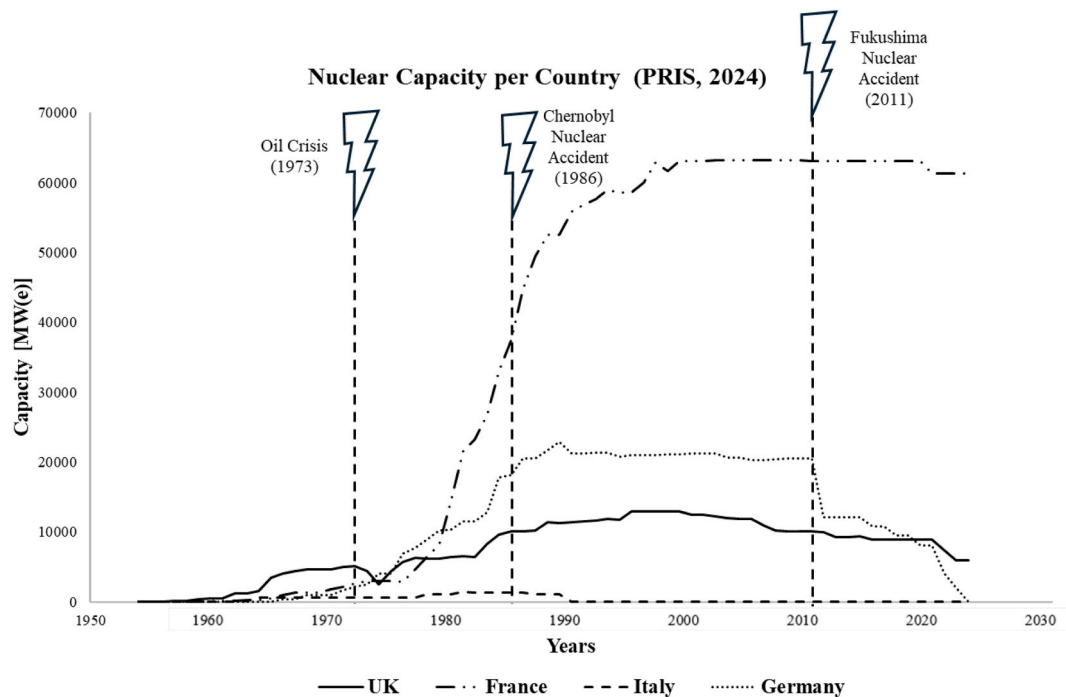


Fig. 2. Capacity installed trajectories following exogenous events.

although relevant during the early stages of development or expansion, tend to lose significance once the system reaches a state of consolidation. Consequently, not all the factors play a key role in shaping the momentum (Hughes, 1987) of nuclear LTSs. For this reason, we include in Table 2 only those that determined the momentum of the nuclear LTSs analyzed. This framework is not intended to be exhaustive, but rather serves as an analytical lens to understand the dynamic interplay of these core variables, acknowledging they are embedded within deeper and unique national historical contexts.

Emphasizing the necessary dynamic interplay and alignment between social and technical elements, we categorized these factors into five dimensions: socio-economic, technological, political, socio-cultural, and environmental. We now present the three factors that often emerged from our data, which are also relevant for the context examined.

Political Support emerged as a foundational factor for nuclear LTSs momentum. In France, centralized political leadership and dirigiste governance ensured consistent governmental backing, insulating the system from societal and political contestation even after nuclear accidents (Andersson and Finnegan, 2024; Sovacool et al., 2019). In contrast, the German LTS suffered from fragmented political structures and the rise of anti-nuclear political actors, such as the Green Party, which ultimately eroded momentum and accelerated the phase-out after Fukushima (McCauley et al., 2018; Renn and Marshall, 2016).

Media Support critically influenced socio-cultural acceptance. In the UK, the nuclear sector actively engaged in reframing nuclear energy as a necessary tool for climate change mitigation, launching strategic media campaigns that reshaped public discourse (Rogers-Hayden et al., 2011). As a result, nuclear power faced limited political opposition, sustaining the system's momentum even amid economic challenges. Conversely, in Italy and Germany, biased and fear-amplifying media coverage after Chernobyl and Fukushima reinforced widespread public skepticism, directly contributing to the delegitimization of nuclear LTSs (Hake et al., 2015; Perko et al., 2019).

Public Financial Resources were crucial for maintaining momentum, particularly after exogenous events. In France, substantial state financing and direct ownership of enterprises such as EDF enabled rapid infrastructure development and shielded the system from private market failures (Andersson and Finnegan, 2024). In the UK, despite the

privatization of British Energy and its financial collapse in the early 2000s (Doyle, 2011; Thomas, 2016), the government's willingness to intervene demonstrated how financial support remained essential for system survival.

The combination of the identified factors determines the system's momentum, reflecting its resistance to change, stability, inertia, and resilience. For this reason, a thorough analysis of these factors allows for an assessment of the system's vulnerability, as well as the estimation of potential future trajectories. Our empirical observations suggest that these factors undergo dynamic evolution over time. However, often, shifts in the configuration of factors are driven by broader cultural or technological developments within national or international contexts. These changes typically unfold gradually and over extended timeframes, making it relatively feasible to detect early signals, anticipate potential trajectories, and, if necessary, intervene strategically.

Fig. 3 generalizes the behavior of nuclear LTSs in response to exogenous events. Empirical observations suggest two distinct scenarios. In the first scenario (on the left), the initial configuration of the system's key factors renders the LTS highly resilient, resulting in limited or no impact on its evolutionary trajectory. In this case, the nuclear LTS continues along its pre-existing path, with no substantial disruption. In the second scenario, by contrast, the exogenous event acts as a tipping point. A poor configuration of factors, resulting in weak LTS's momentum, can trigger a reconfiguration and lead to a destabilization of the system's trajectory. However, empirical evidence indicates that this turning point may lead to two divergent outcomes. On the one hand, the reconfiguration may foster a favorable environment for nuclear technology at the national level, thereby catalyzing increased investments and a rise in installed capacity over time, ultimately leading the system to exceed its previous trajectory. On the other hand, the reconfiguration may negatively impact these factors, creating a hostile environment for nuclear technology, which could result in a significant deviation from the prior trajectory or even lead to a complete phase-out of the technology.

This novel framework helps in understanding how nuclear LTSs can be steered or destabilized depending on their pre-event configuration. In contexts where exogenous events can trigger a tipping point, the path of systemic reconfiguration not only depends on the type of event but also

Table 2
Factors determining the momentum of Nuclear LTSs.

Dimensions	Factors	Sources/References
Socio-economic	Human Resources Availability	(COD #4 – Consuming Agents) (COD #12 – Studying), (COD #13 – Working), (COD #37 – Technical Human Resources Availability), (Markard and Truffer, 2006)
	Public Financial Resources	(COD #1 – Government and Public Entities), (COD #8 - Financial Relation), (COD #10 - Subsidize), (COD #57 - Scarce Financial Resources), (Burke, 2010; Sommers, 1980; Brutschin et al., 2021)
	Lenders and Private Investors support	(COD #8 - Financial Relation) (COD #11 - Consortium) (COD #14 – Liberalization), (COD #15 – Privatization) (COD #57 - Scarce Financial Resources), (Sommers, 1980; Brutschin et al., 2021)
	Developed nuclear supply chain	(COD #2 – Production, Distribution and Transmission Agents) (COD #6 – Market Dynamics) (COD #7 – Direct Control) (COD #9 – Ownership) (COD #42 - Industrial Supply Chain), (Stirling and Johnstone, 2018; Adamantiades and Kessides, 2009)
	Ability to undertake major projects	(COD #46 - Ability to Undertake Major Projects) (COD #31 - Contextual)
Political	Political Support	(COD #1 – Government and Public Entities) (COD #27 - Constructed) (COD #40 - Political Support) (COD #54 – Politicization), (Neumann et al., 2020)
	Political stability	(COD #1 – Government and Public Entities) (COD #30 – Commodified), (Brutschin et al., 2021)
	Government leadership	(COD #1 – Government and Public Entities), (COD #24 - Dirigisme), (COD #27 - Constructed), (COD #40 - Political Support), (COD #41 - Centralized Decision Making), (Rochlin, 1995; Sovacool and Valentine, 2010)
	Commitment to energy independence and security	(COD #17 - Securitization), (COD #38 – Long-Term Perspective), (COD #39 - Commitment to Energy Independence and Security), (Fuhrmann, 2012; Gourley and Stulberg, 2013; Cherp et al., 2017; Adamantiades and Kessides, 2009)
	Long-term planning	(COD #38 – Long-Term Perspective) (COD #41 - Centralized Decision Making) (COD #54 – Politicization)
Technological	Centralised Market	(COD #6 – Market Dynamics) (COD #7 – Direct Control) (COD #43 - Centralized Market Structure), (Rochlin, 1995; Sovacool and Valentine, 2010)
	Radioactive Waste Management	(COD #51 - Waste Management Challenges), (Adamantiades and Kessides, 2009; Brutschin et al., 2021)
	Increasing Electricity Demand	(COD #3 – Consuming Agents) (COD #44 – Increased Electricity Demand), (Markard et al., 2020)
	R&D on nuclear technologies	(COD #1 – Government and Public Entities) (COD #12 - Studying)
	Adequate Grid capacity	(COD #2 – Production, Distribution and Transmission Agents) (COD #49 – Grid Capacity), (Stirling and Johnstone, 2018)

Table 2 (continued)

Dimensions	Factors	Sources/References
Socio-cultural	Media Support	(COD #4 – Others) (COD #56 - Mediatiation) (COD #30 – Commodified) (COD #34 - Contested)
	Siting – local communities support	(COD #4 – Others), (COD #13 – Working), (COD #52 - Site Selection Difficulties), (Laird and Stefes, 2009; Adamantiades and Kessides, 2009)
	Citizens Support	(COD #3 – Consuming Agents), (COD #4 – Others), (COD #35 - Collective) (COD #45 – Citizens Support), (COD #50 – Anti-nuclear Sentiment), (Laird and Stefes, 2009; Sovacool and Valentine, 2010; O’neil, 1999; Starr and Whipple, 1984)
	Public awareness	(COD #31 - Contextual), (COD #58 - Low Public Interest and Awareness), (Adamantiades and Kessides, 2009)
Environmental	Environmental Sentiment	(COD #4 – Others), (COD #31 - Contextual), (COD #34 – Contested), (COD #47 - Environmental Sentiment), (Laird and Stefes, 2009; Stern, 2007)
	Primary energy sources scarcity	(COD #5 - Policy Imposition), (COD #53 - Availability of Alternative Energy Sources), (COD #55 – Environmental Concerns), (Huenteler et al., 2014; Lauber and Jacobsson, 2016; Brutschin et al., 2021)

on the momentum of the nuclear LTS at the moment of occurrence. This suggests that exogenous events should not be understood merely as shocks to which systems passively respond but rather as windows of opportunity or threat during which decision-making processes influence long-term trajectories. Our findings also suggest that resilience in nuclear LTSs is not a fixed attribute, but an emergent property conditioned by historical path dependencies and, therefore, dynamically evolving over time.

7. Conclusions

The global energy transition, driven by the dual goals of climate mitigation and energy security, positions nuclear power as a key technology whose deployment depends on the development of nuclear complex LTSs. Trajectories of nuclear LTSs have historically exhibited considerable heterogeneity across nations, even among those with comparable technological, demographic, and political profiles. Addressing this phenomenological issue, this paper investigates the factors that shape the resilience and continuity of nuclear LTSs by adopting a multiple-case study approach and considering the evolution of nuclear LTSs in the UK, France, Germany and Italy. This is also relevant since existing research has examined the phases of growth and consolidation in nuclear LTSs, but a significant gap remains in understanding their momentum (i.e., the resistance to change and resilience of nuclear LTSs).

Analyzing the historical evolution of such nuclear LTSs, we found that in Italy and Germany, system destabilization was associated with exogenous events, although such events rarely act in isolation and change can also occur without them. We focused on three events that functioned as windows of opportunity or threat for trajectories of nuclear LTSs: the 1970s oil crisis, the Chernobyl nuclear accident, and the Fukushima nuclear accident. The comparative analysis demonstrates that the resilience and trajectories of nuclear LTSs are not determined solely by the nature or magnitude of exogenous events but rather by the

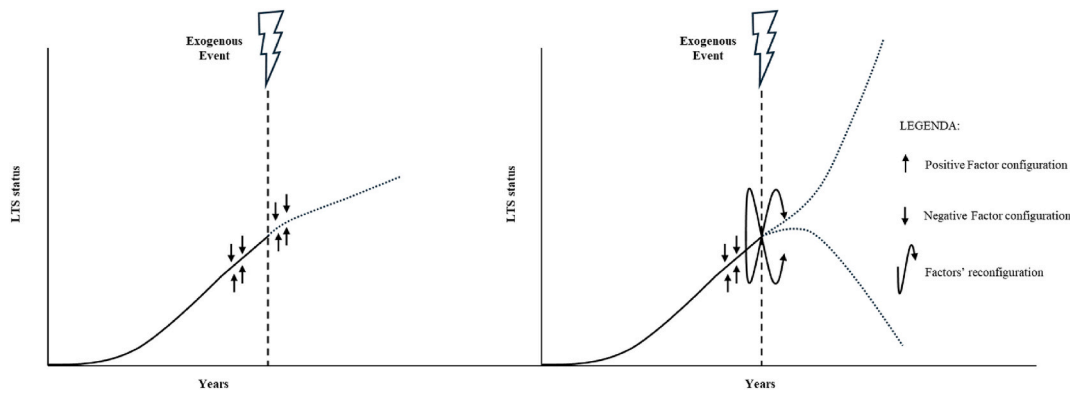


Fig. 3. Generalisation of nuclear LTS trajectories following exogenous events.

pre-existing configuration of key socio-technical, political, economic, cultural, and environmental factors that shape system momentum. By operationalizing the concept of nuclear LTS momentum, detailing an accurate list of underlying factors, this paper contributes a novel framework to the literature on LTSs development and resilience. This study identifies a set of 21 factors that have shaped the evolution of nuclear LTSs in four countries, but these should not be seen as an exhaustive list.

Our findings underscore that momentum is not a static property but an emergent outcome of dynamic alignments between various enabling factors. In systems where this alignment is strong, as in the case of France and, to a lesser extent, the UK, nuclear LTSs exhibited a high degree of resistance to exogenous events, enabling continued development and institutional stability even in the face of global nuclear accidents or economic strain. In contrast, in countries where these factors were weakly aligned or fragmented, as exemplified by Germany and Italy, external events catalyzed structural reconfigurations that ultimately led to the phase-out of nuclear LTSs.

This comparative analysis reveals that centralized governance and sustained political support, as seen in France and the UK, were crucial in maintaining nuclear LTS momentum. In contrast, decentralized systems in Germany and Italy were more prone to destabilization following nuclear accidents. Public perception and media framing also played a crucial role, with negative coverage and direct democratic tools amplifying opposition in Germany and Italy. In contrast, strategic communication in France and the UK helped sustain public support. Finally, infrastructure readiness and institutional maturity determined whether exogenous events were absorbed or became turning points, with France effectively consolidating its nuclear LTS and Italy failing to do so.

These findings are crucial because they demonstrate that, while much of the research on nuclear energy rightly focuses on improving reactor efficiency, safety, reliability, and cost-effectiveness, the potential impact of exogenous events on the broader system should not be underestimated. In other words, even if governments and industry succeed in developing the most advanced technologies within the shortest timeframes and at the lowest costs, many other factors must still be considered. For this reason, the list of key factors we identified offers a valuable tool for policy analysis, enabling policymakers to assess the current momentum of nuclear LTSs and identify potential vulnerabilities or leverage points. Moreover, rather than viewing exogenous events solely as crises, this perspective encourages a proactive stance: investing in governance stability, public trust, and media strategies to build adaptive capacity. Understanding the systemic momentum of a nuclear LTS provides insight into both its resilience to disruption and its potential for transformation. Furthermore, our framework acknowledges that significant reconfigurations can also be driven by purely endogenous dynamics, without the catalyst of an external shock, as the case of Austria's 1978 referendum demonstrates. While such cases are outside the comparative scope of this study, they reinforce our core argument

that systemic change ultimately depends on the internal configuration of the LTS itself and open the field for further research. While our analysis deliberately focused on a set of purposefully selected exogenous events to enable controlled cross-national comparison, we acknowledge that other significant events and systemic dynamics also shape the resilience and trajectories of nuclear LTSs. Future research should therefore expand the scope of inquiry to encompass a broader range of events, such as major national political transitions, geopolitical realignments, or shifts in global energy markets, that may intersect with and reconfigure system trajectories. Recent developments in Germany during the energy crisis triggered by Russia's invasion of Ukraine illustrate how such geopolitical shocks can reopen nuclear debates even in countries with a long-standing phase-out policy. The short-term lifetime extension of three reactors shifts in public opinion, and renewed political controversy suggests that the stability of nuclear LTS trajectories may be more contingent on contemporary geopolitical and economic pressures than previously assumed, offering a promising avenue for future comparative research.

In addition, historically grounded elements, including wartime experience, Cold War dynamics, military–civilian nuclear interlinkages, energy sector interdependencies (e.g., oil and gas with nuclear), and variations in resource endowments, represent potentially influential factors that merit systematic consideration to enlarge the list of factors shaping the momentum of nuclear LTSs identified. Explicitly leaving room for such additional variables reinforces our central claim that resilience in nuclear LTSs is not a fixed attribute; rather, it emerges from historically embedded path dependencies shaped by the interplay of multiple, context-specific determinants.

CRediT authorship contribution statement

Giacomo Dei: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giorgio Locatelli:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Caterina Francescangeli:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Sara Nanni:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

We confirm that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere. All authors have read and approved the manuscript, and there are no conflicts of interest to declare.

The authors declare that they have no financial interests or personal relationships that could have appeared to influence the work reported in

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Annexes

Table 3

Themes and codes identified in the Thematic analysis

Themes:	Codes:	Themes:	Codes:
Agents	Government and Public Entities Production, Distribution, and Transmission Agents Consuming Agents Others	Material Cultures	Constructed Construed Conforming Commodified Contextual Contradictory Closed Contested Collective Chaotic
Relations	Policy imposition Market Dynamics Direct Control Financial Relation	Enablers	Technical Human Resources Availability Long term perspective Commitment to energy independence and security Political support Centralised Decision-making Industrial Supply Chain Centralised Market Structure Increase Electricity Demand Citizens Support Ability to Undertake Major Projects Environmental Sentiment Design Standardisation Grid Capacity
Structures	Ownership Subsidize Consortium	Barriers	Anti-Nuclear Sentiment Waste Management Challenges Site Selection Difficulties Availability of Alternative Energy Sources Politicization Environmental Concerns Mediatiation Scarce Financial Resources Low Public Interest and Awareness
Processes	Studying (R&D) Working Liberalization Privatization Environmentalism Securitization Mediatiation Municipalisation National Prestige Necessitation Responsibilisation Relativisation Dirigisme Volantarisme Politicization		
Tippling Points	Nuclear Accident Energy Market Disruption		

Data statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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