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Failing the formative phase: The global diffusion of nuclear power is limited by national markets

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ABSTRACT

Understanding the role of technology characteristics and the context in the diffusion of new energy technologies is important for assessing feasibility of climate mitigation. We examine the historical adoption of nuclear power as a case of a complex large scale energy technology. We conduct an event history analysis of grid connections of first sizable commercial nuclear power reactors in 79 countries between 1950 and 2018. We show that the introduction of nuclear power can largely be explained by contextual variables such as the proximity of a country to a major technology supplier ('ease of diffusion'), the size of the economy, electricity demand growth, and energy import dependence ('market attractiveness'). The lack of nuclear newcomers in the early 1990s can be explained by the lack of countries with high growth in electricity demand and sufficient capacities to build their first nuclear power plant, either on their own or with international help. We also find that nuclear accidents, the pursuit of nuclear weapons, and the advances made in competing technologies played only a minor role in nuclear technology failing to be established in more countries. Our analysis improves understanding of the feasibility of introducing contested and expensive technologies in a heterogenous world with motivations and capacities that differ across countries and by a patchwork of international relations. While countries with high state capacity or support from a major technology supplier are capable of introducing large-scale technologies quickly, technology diffusion to other regions might undergo significant delays due to lower motivations and capacities.

1. Introduction

Meeting climate targets requires a rapid expansion of low-carbon technologies [1], the feasibility of which is debated [2–4]. One way of exploring this feasibility has been to examine the historical adoption of new energy technologies in terms of growth rates, duration of transition, length of the formative phase, and the experience rates, metrics that can also be used for assessing future scenarios [5–13,42]. The literature on this topic has linked the speed of transition to various technology characteristics, such as granularity [14], complexity, and standardization [15].

This approach has also been used to understand the potential of various technologies to mitigate climate change. There have been debates on the potential role of nuclear power, especially on whether it has grown faster or more slowly than renewables [16–18] and how its costs have evolved over time [19–24]. A closely related debate concerns the reasons for the rapid expansion of nuclear power in many national markets, such as Sweden [25] and France [26], and its subsequent global stagnation. According to an explanation rooted in the Technology Innovation System (TIS) concept, the roots of the decline in nuclear power use stem from its slowness to innovate, decreasing diversity, poor construction performance, the occurrence of major accidents, and the progress made in competing technologies, such as wind and solar power [27]. The same study also points out that the recent liberalization of electricity markets has made nuclear power uncompetitive except in non-liberalized markets like Russia and China [27].

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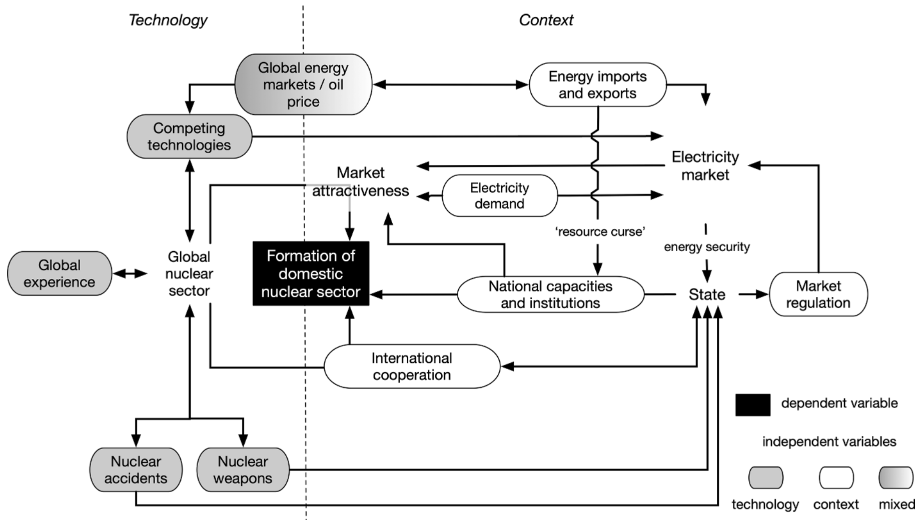

Fig. 1. Mechanisms of the formative phase of national nuclear power sectors and hypotheses used in the analysis.

The various debates invoke two different explanations for the decline of nuclear power: i) it is being globally outcompeted by other technologies, and ii) it is unsuitable for many national markets. Despite these explanations being closely linked, they have fundamentally different implications for future low-carbon energy transitions. If nuclear power has inherent characteristics that make it inferior to its competitors, then it has little or no role to play in climate mitigation. If, on the other hand, the liberalization of electricity markets does stand in its way, nuclear power can still retain its role in climate mitigation scenarios where electricity markets are regulated. Furthermore, the very presence of niche markets and newcomers [28,29] points to another competing theory as to why nuclear power has stagnated. It was not that the technology ran into any insurmountable problems: it simply ran out of markets in which to flourish. In support of this explanation, Jewell [30] and Cherp et al. [31] argue that the growth of nuclear power requires high growth in electricity demand, while Johnstone and Stirling [21] point out that the divergence of nuclear trajectories can be better explained by some of the features of political systems rather than by the internal characteristics of the nuclear power sector. This explanation also has implications for future low-carbon energy transitions: if in the future there is an increase in the number of suitable national markets (e.g., with high growth in electricity demand and high national and international capacity), nuclear power could be introduced into new countries and play a significant role in climate mitigation.

To contribute to this debate, we seek to conceptually disentangle the effect of technology characteristics from the effect of the socio-economic context surrounding the diffusion of nuclear power. We hark back to the pioneering scholarship of Zvi Griliches [32] who identified two key contextual factors shaping technology adoption: market attractiveness and ease of diffusion. This early work has not been systematically followed up in the recent literature on technology diffusion, possibly because it requires the focus to be shifted from technology innovation and socio-technical systems to other (techno-economic and political) societal systems in which new technologies are embedded. This, in turn, calls for engagement with research areas other than technology diffusion studies [33]. On the other hand, comparative studies of political science and economic history have extensively documented the effect of socio-economic and political factors on the globally unequal adoption of nuclear power [34–38] and its competitors [39], but have failed to reach a consensus on how these effects can be generalized (see Bourcet [40] on renewables). We believe that just as the shortcomings of technology diffusion studies can be remedied by more systematic attention to contextual factors, so the shortcomings of the comparative studies can be overcome by more systematic attention to technology diffusion theories and in particular to the phases of the technology lifecycle [41,42].

To explain the dynamics of nuclear power, taking into account both its technological characteristics and the characteristics of the receiving context, we ask why the ascent of nuclear power stalled. We test two main explanations. The technology explanation: that nuclear power stalled because it was taken over by competitors and was prone to accidents, and the contextual explanation: that nuclear power stalled because it ran out of sufficiently attractive markets where it could easily diffuse. In other words, the number of countries with both the capacity and the motivation to introduce nuclear power declined over time.

In our analysis we follow Markard et al. [27] who focus on a specific phase of the nuclear power technology lifecycle. In contrast to Markard et al. [27], however, we focus not on whether and why nuclear power has recently been declining, but rather what factors limited its use in the first place to the Organisation for Economic Co-operation and Development (OECD), the former Council for Mutual Economic Assistance (COMECON), and what has later become known as G20 countries. By studying the historic ascent of nuclear power, we identify the factors that have determined whether, and how early, a particular country would introduce nuclear power.

The study of the ascent of nuclear power requires us to focus on the formative phase of the technology lifecycle in individual countries. As an indicator for successful completion of the formative phase we use the occurrence and the time of the grid connection of the first sizable commercial nuclear reactor in 79 countries with a sufficiently large electricity grid over 70 years (1950–2018). We thus combine an analysis of technological characteristics with an analysis of the characteristics of the national and international contexts (i.e., those that facilitated or hindered technology diffusion). Overall, we find that contextual characteristics such as demand growth, the size of the economy, import dependence, and foreign policy alignment are more robust explanations for the historical trends of nuclear technology introduction than technology-specific characteristics, such as major accidents, global experience with nuclear technology, pursuit of nuclear weapons, or advances in competing technologies. This knowledge is critical for understanding the prospects not only of nuclear power, but also of other 'market-anchored' [43] low-carbon technologies which need to diffuse from their 'core' in industrialized countries of the OECD to other regions.

In Section 2, we systematically identify the mechanisms operating at the formative phase of nuclear power uptake and propose a framework for comparing these across countries and over time. Section 3 explains the method and Section 4 contains the results of the statistical analysis of

Table 1
Key technology specific mechanisms.

Technological context	Hypotheses
1. Global experience	Accumulated global experience makes nuclear power more accessible to newcomer countries
2. Nuclear accidents	Nuclear accidents make nuclear power less attractive to newcomer countries
3. Link with nuclear weapons	Association with nuclear weapons can facilitate mobilization of domestic resources for nuclear power in countries pursuing nuclear weapons or trigger international opposition, even to civil nuclear programs in such countries
4. Market competitiveness	Decline/increase in the competitiveness of other technologies makes nuclear power more/less attractive to newcomer countries

Table 2
Key context specific mechanisms.

Local Context	Hypotheses
5. Socio-economic characteristics	Countries that experience high demand growth, have a large economy size and high income per capita, are not major energy exporters, and are politically stable; are more likely to introduce nuclear power.
6. International cooperation	Countries that are politically aligned with and economically tied to at least one key nuclear supplier or global power (USSR/Russia and USA) are more likely to introduce nuclear energy.
7. Political and regulatory regimes	Countries with a liberalized power market are less likely to introduce nuclear energy. The level of democracy level could have both positive and negative effects on the probability of introducing nuclear energy.

the timing of the connection of the first (sizable) reactor to the grid using logistic regression. In Sections 5 and 6, we interpret the findings of this analysis in terms of the patterns of global diffusion of nuclear power and propose an explanation of why this process has stagnated and what the future prospects of nuclear energy may be.

2. Analytical framework and hypotheses

2.1. Formation of national nuclear power regimes

The uptake of a new technology both globally and in individual national markets follows several distinct stages of a technology lifecycle, commonly called the *formative*, *growth,* and *maturity* stages [41,44] each driven and constrained by their own mechanisms [8,13,41,42,44–46]. This means that the factors explaining the national differences in technology use could vary from one phase to another.

In this paper, we specifically focus on the initial, formative phase of nuclear power uptake. At this phase, the national commitment to introducing nuclear power is established, the necessary institutions are set up, concrete design and siting plans are drawn, financing is secured, and domestic manufacturing, or more often overseas procurement of necessary equipment and expertise, is arranged. Finally, the first nuclear power plant is constructed and starts supplying energy to the grid. At this point, a country is likely to have created a socio-technical regime associated with nuclear power, capable of self-reproduction and evolution during the subsequent phases of technology lifecycle. We provide more details in Section 3.2 on how the accomplishment of the formative phase is operationalized.

The formation of a domestic nuclear sector (the dependent variable) is affected by many factors which, for the purposes of this analysis, are categorized into two groups: technological characteristics and receiving context characteristics, as shown in Fig. 1 and discussed in the next two sections. Overall, we group all key explanatory factors, identified in the existing literature, into four key mechanisms at the technological level and three key mechanisms at the context-specific level.

2.2. Technology-specific mechanisms shaping the introduction of nuclear power

We explore four key technology-specific mechanisms (Table 1) which could affect the introduction of nuclear technology. As the technology evolves over time and becomes more mature, we expect it, through accumulated ***global experience,*** to be more accessible to newcomer countries [8,15].

A specific characteristic of nuclear technology is significant safety concerns and the possibility of ***major accidents*** such as those at Three Mile Island (TMI) (USA, 1979), Chernobyl (USSR, 1986) and Fukushima (Japan, 2011). Fuhrmann [47] and Gourley & Stulberg [36] find a statistically significant impact of TMI and Chernobyl on the construction of nuclear power plants. On the other hand, Csereklyei et al. [35] did not find the accidents to have any delaying effects on nuclear power plant construction, but they did find the Chernobyl accident to negatively affect how many new power plants were constructed at the global level [34].

Another feature of nuclear power technology is its close association with the ***pursuit of nuclear weapons*** [27,48,49]. This association could be either enabling, with states that pursue nuclear weapons devoting more resources to nuclear technologies, or constraining, with non-proliferation concerns slowing down nuclear technology diffusion, especially in states geopolitically opposed to the core nuclear technology countries. Fuhrman [47] found that neither the presence of nuclear weapons nor the ratification of the Nuclear Non-Proliferation Treaty (NPT) correlates with the construction of nuclear power plants. Neumann et al. [37] found that the possession of nuclear warheads increases the probability of operating nuclear power plants almost fourfold; this is similar to Gourley and Stulberg [36], who found that the possession of nuclear weapons had statistically significant effects on the use of civil nuclear power during the Cold War era. Jewell [30] observed that relatively poorer and smaller economies, such as Pakistan, were able to launch nuclear power programs if they were simultaneously pursuing the development of nuclear weapons.

Nuclear power evolves in ***competition*** with other electricity generation technologies. One outcome of this competition is the change in the share of different electricity generation technologies over time. The first factor in this competition is the economic cost of technologies. Analyses of the evolution of costs related to the construction of nuclear power reactors present conflicting conclusions [7,23,50]. This is partly because the estimation of costs over time and across different markets is challenging due to the lack of transparent data and the many different methodologies used to calculate the economic costs. In the most recent study of the International Energy Agency–Nuclear Energy Agency (IEA–NEA), the overnight cost for nuclear ranges from 2157 to 6920 $/kWe, but this was evaluated only for eight countries [51, p. 43]. In addition to the wide range of construction costs, nuclear power cost estimates are further complicated by cost uncertainties related to operating, insurance, decommissioning and waste management.

Technologies compete not only on economic costs but also on characteristics such as ease of introduction and operation, reliability, emissions, contribution to economic development, and energy security. When nuclear was introduced in the post-war period, global electricity generation was dominated by hydro, coal, and oil-fired generation. In several industrialized countries, nuclear was promoted as a response to increasing oil prices to replace imported oil in power generation [48,52]. According to Csereklyei et al. [35], higher oil prices (which correlate with prices of other fossil fuels, see Fig. A1) led to faster construction of nuclear power plants (see also Markard et al. [27]).

Moreover, several new electricity generation technologies have emerged or expanded and could plausibly have outcompeted nuclear power. These include natural gas (enabled by such innovations as long-distance pipelines, liquefied natural gas (LNG), and more recently, fracking, wind, and solar power (see Fig. A2 in the Appendix).

Table 3
Independent variables.

Mechanism	Variables	Operationalization	Notes/Sources
1. Global experience	Cumulative reactor starts	The number of nuclear reactor starts in a given year and all preceding years	IAEA PRIS [79]
2. Nuclear accidents	Occurrence of a major nuclear accident	Binary coding: 1 in the year of the accident + 2 consecutive years after TMI (1979), Chernobyl (1986), Fukushima (2011)	Own coding/additional specifications similar to Csereklyei [34]
3. Nuclear weapons	Presence of a nuclear weapons program	Binary coding: 1 in all years the year after the nuclear weapons program start year	It is assumed that no new countries started a nuclear weapons program post 2006, the year from which the historical data for the exact start year of the nuclear program were taken, Jo and Gartzke [81]
4. Market competitiveness	Oil price (log 2019$)	Historical oil price in 2019 $, transformed as a natural logarithm	Taken from the most recent data from BP [92]
	Shares of gas	Global shares of gas in electricity generation	Calculated based on World Energy Balances IEA data [85]
	Shares of solar and wind	Global shares of solar, and wind in electricity generation	Calculated based on World Energy Balances IEA data [85]
	Shares gas, wind and solar	Global shares of gas, solar, and wind in electricity generation	Calculated based on World Energy Balances IEA data [85]
5. Socio-economic characteristics	OECD	Binary: see section 3.3 for a detailed explanation	As a proxy for key national characteristics
	High electricity growth	Binary: 1 if the growth is >2 TWh/y in 3 consecutive years	Historical data taken from Mitchell [84] and more recent data from IEA.
	Import dependence/ Oil producer	Binary: 1 if dependence >25%/Binary: 1 if oil exports exceed 10% of GDP in a given year	IEA, calculations based on Cherp et al. [42]/major oil exporter categorization taken from Colgan [86]
	Economy size	Real GDP in US dollars. Transformed as a natural logarithm	Historical data taken from Gleditsch [88] and more recent data from the World Bank [87]
6. International cooperation	OECD	Binary: see section 3.3 for a detailed explanation	As a proxy for key international characteristics
	COMECON	Binary: 1 for the year a country becomes a COMECON member and subsequent years	As a proxy for key international characteristics
	Aligned with the USA	This variable ranges from 1 (complete foreign policy similarity) to −1 (complete dissimilarity) based on UN voting data	Weighted s scores based on the calculations from Chiba et al. [82] and Signorino and Ritter [83]
	USSR dissolution	Binary (1 after 1991)	
7. Political and Regulatory Regime	OECD	Binary: see section 3.3 for detail	As a proxy for stable and liberalized markets after the liberalization wave
	Democracy level/ Political stability	Ranges between −10 (full autocracy) to 10 (full democracy)/ Binary: 1 if a severe crisis occurs in the preceding five years.	Marshall and Jaggers [89], update version of PolityV/PITF
	Power market liberalization	Ranges from 0 to 8 from non-liberalized to completely liberalized power sector	Data for developed countries based on Erdogdu [91] and developing countries based on Urpelainen and Yang [90]

2.3. *Context-specific mechanisms shaping the introduction of nuclear power*

The central mechanism by which the societal context affects the introduction of nuclear power is state action [38]. This means that the introduction of nuclear power requires a high level of state motivation and capacity [30] and therefore countries able to introduce nuclear power should have certain characteristics, which we group into the following categories: (i) socio-economic characteristics, (ii) international cooperation, and (iii) political and regulatory regimes (see also Table 2).

2.3.1. *Socio-economic characteristics*

States' energy policies are motivated by the need to ensure a secure supply–demand balance [53]. In particular, ***high import dependence*** might motivate a state to invest in a 'quasi-domestic source' [31]. Existing studies do not provide conclusive evidence of how the dependence of energy imports affects the use of nuclear power [35,47,54]. For fossil fuel producers, the level of motivation to invest in nuclear power might be relatively low, as such states do not experience significant energy security concerns. Additionally, some major energy producing countries may suffer from the so-called "resource-curse" [55], which reduces their capacity to promote complex technological developments. Finally, it is not uncommon for major energy producers to subsidize domestic electricity [56], which could make non-fossil power sources unprofitable for them.

Energy security concerns may also arise from rapid ***electricity demand growth*** [57]. Jewell [30] observed that nuclear power has been introduced following extraordinary growth in electricity demand; Cherp et al. [31] also showed that the rapid expansion of nuclear power in Japan—but not in Germany in the 1990s—is explained by rapid growth in electricity demand. Growing electricity demand not only motivates states to support nuclear power, but also makes national power markets attractive to international investors (Fig. 1). Markard et al. [27] remark on high demand growth in emerging economies as potentially stimulating expansion of nuclear power. However, a systematic evaluation of the connection between electricity demand growth and nuclear power is lacking in the literature.

Apart from motivation, the ability of states to achieve their goals depends on national **capacities**. Markard et al. [27, p. 3] argued that nuclear power is a complex technology 'which demands skilled labor and specific technological and organizational competences'. Wealthier economies may find it easy to facilitate the launch of nuclear programs [30,49] through, for example, state-funded research and development [27] combined with provision of state subsidies for individual nuclear plant construction [35,36,47]. Moreover, larger and richer economies attract investors, suppliers, and project developers, facilitating diffusion of new technologies through 'market attractiveness' [32]. Another capacity variable is political stability, which, according to Jewell [30], affects the launch of new nuclear programs, as illustrated by the case of Turkey, where political instability has derailed at least four different attempts to build a first nuclear power plant from the 1950s onwards [58]. It is thus plausible to assume that among the factors facilitating the introduction of nuclear power are ***larger size of the economy***, ***higher income*** and ***political stability***.

2.3.2. *International cooperation*

Nuclear power, like any technology, was introduced first by early adopters (the core) and then taken up by latecomers (the rim and periphery) [7,59,60]. Technological diffusion involves transfer of artifacts (e.g., supply of nuclear reactors) and also knowledge (e.g., through training of engineers and provision of guidelines to regulators). The

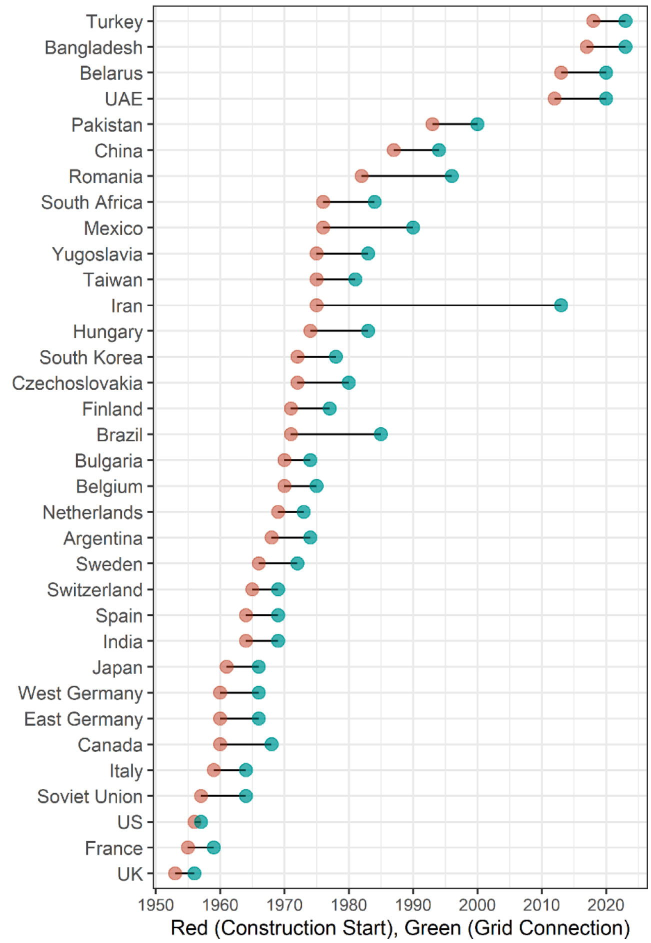

Fig. 2. Take-off Sequence of the first sizable (not research) nuclear reactor. *Note:* Construction start and grid connection of reactors marking the accomplishment of the formative phase are based on data from IAEA country profiles. For the four "newcomers" Turkey, Bangladesh, Belarus, and the UAE, years of grid connection are current estimations based on IAEA country profiles. The first nuclear reactor in the UAE was connected to the grid in August 2020; the reactor in Belarus started commercial operations in March 2021 but has frequent emergency shutdowns. The Figures refer to the information available as of April 2021[80].

nuclear supply chain is extremely concentrated [61,62], which is also reflected in the structure of international nuclear cooperation agreements [63]. Existing studies show that nuclear newcomers have often benefited from technological assistance from countries with existing nuclear power programs (see e.g., Jewell and Ates [58] on Turkey; Choi et al. [64] for South Korea; Price [65] for France; and Smith and Rose [66,67] for Japan). Geopolitical considerations affecting the diffusion of civil nuclear power have been stressed by many authors [27,61,68]. However, a statistically significant link between a country's position within the international system and the introduction of nuclear power has not been found in the case of defense pacts with major suppliers [47] or trade openness [36]. As early adopters of nuclear energy were concentrated in Western Europe, North America, and the USSR we hypothesize that ***foreign policy alignment with*** the USA and the USSR could be a proxy for easier diffusion of nuclear power.

2.3.3. Political and regulatory regime

As a technology relying strongly on state support, nuclear power depends on the state's institutions and politics, not only on its economic capacities and geopolitical position. One such characteristic is the ***level of democracy.*** Advanced democracies have high levels of administrative capacity but at the same time might struggle to implement certain policies in the face of a high number of veto players [69] and competing interests. Jasper [70] and Sovacool and Valentine [38] argue that more centralized governments, such as France, are more easily able to deploy nuclear power, even against citizens' wishes, than more decentralized systems such as the United States. Stirling and Johnstone [21] advance a similar argument, namely, that a different "quality of democracy" in the UK is responsible for its decision to resume nuclear power plant construction, in contrast to Germany. While Gourley & Stulberg [36] do not find the level of democracy to statistically affect whether a country starts nuclear power plant construction, a more recent analysis [37] points out that democracy makes it less likely for a country to construct its first (but not subsequent) nuclear power plants. Csereklyei et al. [35] find that democracy *accelerates* the construction of nuclear power plants, while Thurner et al. [71] find that *autocracy* has an accelerating effect. It has been argued that, besides the quality of democracy—and given the capital intensity, risks, and long pay-off times of nuclear power - electricity market **liberalization** may have made the introduction of nuclear power more challenging [27]. We thus also consider the levels of power market liberalization in our analysis.

Climate change mitigation is also mentioned among other political factors associated with the uptake of nuclear power [27]. Reframing nuclear energy as a sustainable energy technology is however a relatively recent phenomenon [72] that covers only a small part of the overall time period considered in this study. Whether framing nuclear technology as an important climate mitigation strategy is a relevant factor could be explored in more detail by conducting case studies of nuclear newcomers (Belarus, Turkey, United Arab Emirates [UAE] and Bangladesh). One more factor mentioned by Markard et al. [27] and several other authors are social movements [73]. Social movements have indeed played a role in some cases such for example the referendum in Austria [74], where nuclear program was stopped after a nuclear power plant was built. Moreover, a rigorous analysis of social opposition to nuclear power highlights the importance of political circumstances for a social movement to be successful [75]. A more systematic analysis of social opposition to nuclear power thus deserves a separate study, using more fine-grained qualitative methods and case studies.

3. Research design

3.1. Sample and period selection

Previous studies on national differences in the use of nuclear energy were conducted either only on countries with existing nuclear power programs [30,38] or on the maximum possible number of countries [36,37,71]. The former studies do not allow the differences between countries with and without nuclear energy programs to be analyzed, while the latter suffer from incorporating many economies that are too small to even accommodate a nuclear power plant. To overcome these shortcomings, our sample covers 79 countries including 34 countries with nuclear power (see Appendix Table A2) that (i) have an electric grid capacity of over 1 GW[1] as of 2017, and (ii) have stated an interest in developing a nuclear energy program at some point in time, as documented by the country profiles from the World Nuclear Association [76]. This allows us to include only those countries interested in and, at least in principle, capable of deploying nuclear power. Our observation period starts in 1950, that is, several years before the deployment of the first commercial nuclear reactor in the UK (1956), and ends in 2018 with the most recent available data on some of the key variables included in our analysis (newcomer countries such as Bangladesh, Belarus, Turkey, and UAE are included in samples where we use the year of construction start as the dependent variable, but not where the dependent variable is grid connection (see Fig. 2 and Tables A3 and A4 in the Appendix).

3.2. Dependent variable

In our analysis, we use the timing of the first sizable nuclear power plant as the **dependent variable** signaling the completion of the formative phase of nuclear power in a particular country. Previous studies have defined different thresholds for formative phases of new technologies. For example, Grubler et al. [8] proposed 5 %, while Bento et al. [59] proposed 2.5% of potential market adopters for a wide range of technologies. In a renewable energy context, Cherp et al. [42] proposed 1% of electricity be generated by wind and solar power, while Gosens et al. [77] proposed 100 MW of installed wind and solar power capacity as thresholds for the end of the formative phase. Nuclear power is different in that the relative size of individual plants is typically very large, so that the first plant is likely to exceed both 100 MW and 1% of national electricity production, especially in smaller countries. On the other hand, the complexity of a nuclear power plant and its associated supply chains mean that the start of electricity production from the first nuclear power plant in most cases signals the presence of the necessary technical capacity, investment model, regulations, and other elements of a socio-technical regime and is also the completion of all the "milestones" for the introduction of nuclear power as defined by the International Atomic Energy Agency (IAEA) [78].

We used the IAEA PRIS database [79] to obtain information on the first two reactors established in each country. We used this approach because some countries build their first reactor for research or demonstration purposes but never proceed with the use of nuclear technology in the power sector or delay it significantly. We subsequently compared the size of the reactor to other contemporary reactors and assessed the time interval between the establishment of the first and second reactor. If the first reactor is comparatively small and/or the time interval between the first and second reactors is very long, we use the year of construction or connection of the second reactor as the indicator for when the formative phase of nuclear technology was accomplished (see Appendix Table A1).

Example 1. The UK started with a 49 MW plant in 1956 and had built a second one (49 MW) already by 1957. We thus considered the first reactor built in 1956 as the one marking the accomplishment of the formative phase.

Example 2. Pakistan built its first 90 MW nuclear power plant (NPP) in 1972 at a time when much larger reactors were available and a second 300 MW NPP in 2000. We therefore considered the second reactor, built in 2000, as the one marking the establishment of nuclear power.

Fig. 2 depicts the timing of the construction start as well as the grid connection of the reactors that we consider as marking the accomplishment of the formative phase. The majority of countries started the construction of their first sizable nuclear power plant in the 20-year period between 1960 and 1980, but only three countries (China, Pakistan, and Romania) connected their first reactors to the grid in the 20-year period from 1990 to 2010. Sometimes the grid connection of a nuclear reactor can experience delays as it is most strikingly depicted by the case of Iran, and also by the cases of Brazil, Mexico and China. When presenting our results in Section 4, we focus on the year of the grid connection, but in the Appendix (Table A4), we also present a sensitivity analysis for the year of construction start.

The information on the year and the capacity of the power plants was taken from the country profiles of the IAEA.[1] Additionally, we consulted the information provided by the World Nuclear Association (WNA) and other online resources on (i) territories such as Taiwan or the German Democratic Republic (GDR) which are not documented by the IAEA, and (ii) on all the countries planning to introduce nuclear power before 2025. In this way, we identified four countries ("newcomers") whose first nuclear power plant construction occurred as recently as in 2020/2021 (Belarus and the UAE) or is planned in the immediate future (Bangladesh and Turkey).

3.3. Independent variables

In Table 3 we summarize the variables operationalizing the key mechanisms identified in Section 2. For the *technology specific mechanisms,* we use the cumulative number of NPP construction starts in the world for a given year based on the PRIS database as a proxy for the global experience [79]. For nuclear accidents, we coded the major accidents at TMI, USA (1979), Chernobyl, USSR (1986) and Fukushima, Japan (2011) as one variable, but, in additional model specifications in the Appendix (Table A7) we consider them separately [34]. For nuclear weapons development, we used the dataset created by Jo and Gartzke [81] which indicates the year a country started pursuing nuclear weapons. As a proxy for market competitiveness (see also Section 2.2), we look at the oil prices and the sum of shares of the competing technologies in overall electricity generation.

When tracing *context-specific mechanisms* we first used the non-overlapping grouping of countries into OECD and COMECON members. OECD membership is a characteristic of industrial development, democracy, certain regulatory settings, and economic cooperation with other OECD members. The OECD was founded in 1961; however, its predecessor, the Organization for European Economic Cooperation (OEEC) was established in 1948 to run the US-financed Marshall Plan.[2] We thus coded countries as OECD members before 1961 if they were either members of the OEEC or active foreign aid donors (USA, Canada). We coded the OECD variable starting in the exact year of OECD membership only after the breakdown of the Soviet Union. We also generated a variable which indicates whether a country was a member of the Council for Mutual Economic Assistance (COMECON) during the Cold War period. Membership of COMECON signals economic cooperation

[1] https://cnpp.iaea.org/pages/index.htm

[2] http://www.oecd.org/about/history/.

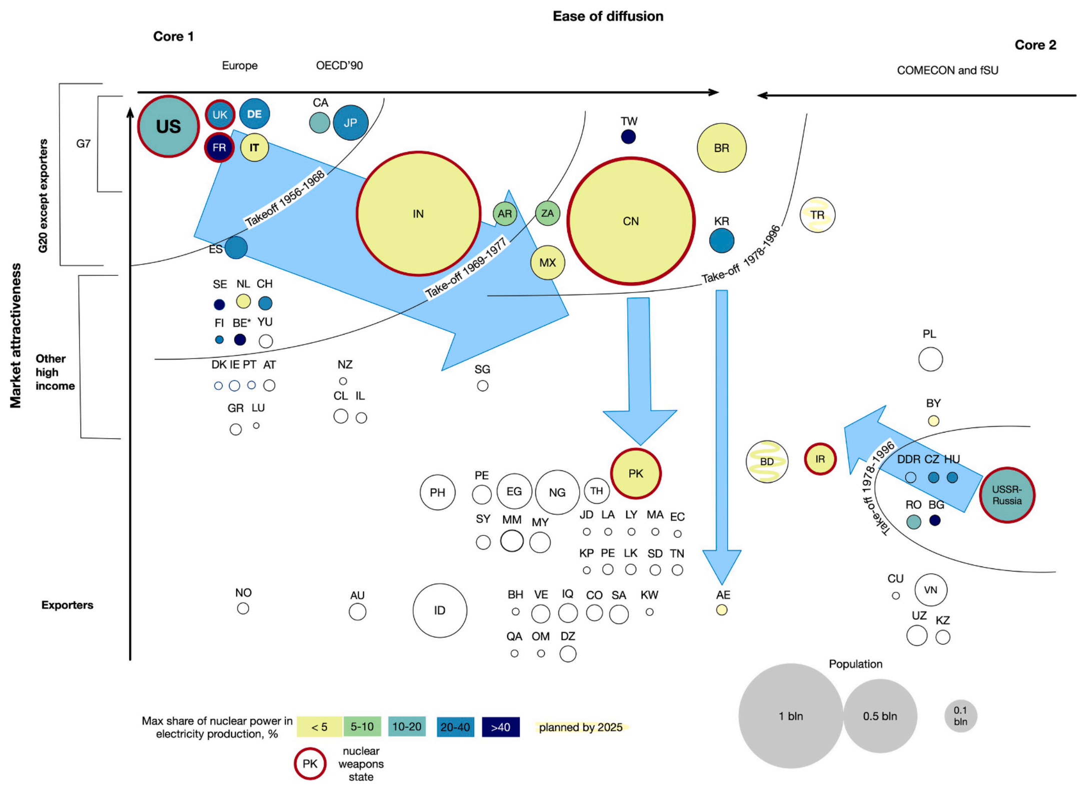

Fig. 3. Sequence of launching nuclear power programs in different groups of countries. *Note:* Circles depict each of the 79 countries analyzed, the size of the circle reflects the population of the country and the shading reflects the peak share of nuclear power in the national electricity supply (white for countries that no longer exist or with no nuclear power and dashed yellow for countries where the first nuclear power plant is expected to become operational between 2020 and 2025). The countries are arranged in sequence according to the time of introduction of nuclear power. The horizontal position reflects the proximity of the country to the two technological 'cores': (a) the USA in the top left-hand corner and (b) the USSR at the bottom right-hand side. The vertical position reflects the attractiveness of countries' markets to nuclear power depending on their size (G20 vs. the rest), the level of income, and the level of fossil fuel exports. The blue arrows show the direction of international diffusion of nuclear power from the two primary cores and from the secondary core in China and South Korea. For the introduction of nuclear power in Finland see footnote. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and political alignment with the Soviet Union. To gain a more precise measurement of external alignment with the dominant suppliers, we also included a measurement of foreign policy similarity, which is frequently used in quantitative international relations research. Specifically, we used the so-called s-scores [82,83]. This variable ranges from 1 (complete foreign policy similarity) to −1 (complete foreign policy dissimilarity).

For electricity demand growth we generated a binary measure and coded it as 1 for high demand growth if a country experienced a growth of more than 2 TWh/y five years ago (here we combined historical data from Mitchell [84] and the most recent data from the IEA [85]); and also if a country was high in terms of import dependences, namely, if it imported more than 25% of fuels used in electricity generation. In additional model specification where we did not include import dependence measure (see Appendix Table A3 and A4), we also looked at whether a country was an oil producer or not according to the definition of oil producer status proposed by Colgan [86]. We measured income levels based on the classification by the World Bank [87], historical gross domestic product (GDP) based on Gleditsch [88], and the most recent World Bank [87] data, which we combined by predicting historical GDP based on values from the World Bank.

Finally, to assess the general political and regulatory regime, we included the levels of democracy [89] based on the most recent data from the PolityV project and, alternatively, we also controlled for political stability based on data from PITF. For the assessment of power market liberalization, we combined data from Urpelainen and Yang [90] and Erdogdu [91], who measure power market liberalization on a scale of 0 to 8, with 0 indicating a lack of any liberalization reforms and 8 standing for completely liberalized markets.

3.4. Model specification

Given the structure of our data (binary dependent variable) and the focus on why some countries are able to establish nuclear programs earlier than others, we utilize a logistic regression model. Given the extensive number of variables that we explore in our analysis, we present a generic version of the logistic function that we use to test our hypotheses (Equation (1)), where p is the probability that a country c will introduce nuclear technology in a year t, conditional on the set of the independent variables X which we discussed in the previous section.

$$p(nuclearonset)_{c,t} = \frac{e^{\beta_0 + \beta_1 X}}{1 + e^{\beta_0 + \beta_1 X}} \tag{1}$$

$$log\left(\frac{p(nuclearonset)}{1 - p(nuclearonset)}\right) = \beta_0 + \beta_1 X \tag{2}$$

We can see from Eq. (1) that for p (*nuclear onset*) an increase in X will not correspond to β_1 (i.e., the effect of β_1 depends on the values of X); however, in Eq. (2), which is a transformed version of Eq. (1), an increase by one unit in X changes the log odds (the left side of the equation) by β_1. The regression output reports β_0 and β_1 from Eq. (2), therefore, in order to understand how one unit increase in X affects the odds, we need to take the natural exponential of the reported coefficients (see also James et al.[93]). In our results section we report regression coefficients (βs) in both the untransformed as well as in the transformed form (odds ratios).

To account for spatial autocorrelations, we cluster standard errors by

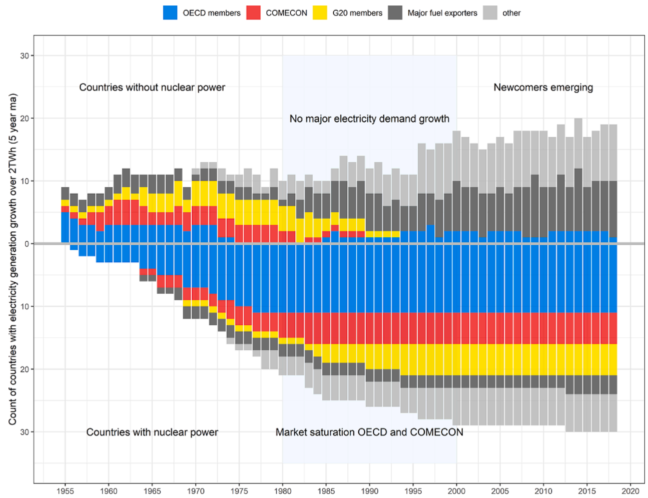

Fig. 4. Characteristics of non-nuclear and nuclear countries (1955–2018). *Note:* The chart depicts the number of countries with demand growth over 2 TWh/ year (as a moving average over 5 years) that did build nuclear power plants (below the horizontal axis) and those that did not establish a nuclear power sector (above the axis). The colors of the bars indicate country groups. Only one country inheriting nuclear power plants from each predecessor state is shown: Russia (from the USSR), Czechia (from Czechoslovakia) and Slovenia (from Yugoslavia). For consistency, the former COMECON states (including the GDR) that became nuclear are carried over the year 1991. We defined OECD and COMECON members as in the quantitative analysis (see Section 3.3) and categorized a country as a major fuel exporter based on World Bank Data, if fuel exports presented more than 20 % of a country's exports in 2018 [95]. G20 members are categorized for the whole historical period rather than just for the period after the formal establishment of G20.

country. To assess the role of time trends, we use polynomial approximation of time (including t, t^2 *and* t^3) as proposed by Carter and Signorino [94] and widely used in applied research of binary events. To further ensure the robustness of our results, we perform a range of different model specifications which we report in the Appendix, including running Cox regressions with our key model specifications from the logistic regression (see Appendix Tables A3–A7).

4. Analysis

4.1. Qualitative exploration

Like other technologies [7,32], nuclear power originated in a handful of nations known as the 'technology core': the USA, the UK, France and the USSR. Its subsequent diffusion was determined by two factors that are well documented for other technologies: the ease of diffusion and market attractiveness [32]. Both factors favored the largest countries in Europe (Germany and Italy) as well as two other G7 members: Canada and Japan. The four core countries plus Canada and Germany were responsible for equipment supplies to all but one[3] of the countries that introduced nuclear power before 1998. Moreover, just four countries (Canada, Germany, USA and USSR/Russia) supplied the first reactors to the majority of other countries. Subsequently, nuclear power spread to less industrialized countries outside Europe, once again favoring more attractive markets in larger countries (future members of the G20) which shows how the size of the economy has been a major factor in the introduction of nuclear power [30]. This wave was almost complete about 40 years after the initial introduction of nuclear power in the first core country. Like other countries in the rim (Canada, Germany), some of the G20 countries developed their own technological capabilities to facilitate further diffusion (e.g., Japan, South Korea and China) creating what might be called 'a secondary core'. Countries with lower economic capacity such as Iran, Pakistan, Belarus, and UAE introduced nuclear power notably later (Fig. 3).

The trends pertaining to context-specific mechanisms, which we identified in Section 2, are depicted in Fig. 4. By looking at the evolution of nuclear technology within the group of countries that experienced a major electricity demand increase (over 2 TWh based on a 5-year moving average) we provide an explanation for the interruption in the spatial diffusion of nuclear technology in the 1980–2000 period, as well as its recent re-emergence. Fig. 4 shows that by the 1980s nuclear power had been introduced into nearly **all** OECD high-income and COMECON countries that had ever experienced high electricity demand growth. The only exceptions were fossil fuel exporters such as Australia and Norway, as well as politically unstable Turkey. In other words, by the early 1990s there were almost no countries in the world that would be both motivated to launch nuclear programs and capable of doing so.

Fig. 4 also illustrates that the number of countries able to accommodate large reactors increased after 2000, but mainly among developing countries and major fossil fuel exporters. The introduction of nuclear power into these countries cannot rely on the TIS built around OECD members, which, as Markard et al. [27] show, is in decline. However, there are signs that another TIS may emerge, dominated partly by suppliers such as Russia [63] and partly by countries acquiring new capabilities as suppliers, such as China and South Korea. Indeed, nuclear programs in three imminent newcomers: Turkey, Bangladesh and Belarus, are being supported by Russia, and the fourth one – the UAE – by South Korea. This TIS will likely serve the potential markets in rapidly growing economies, for example, in Asia, where Markard et al. [27] note that nuclear power plants construction shows no sign of decline.

4.2. Quantitative analysis

To assess which of the trends traced through qualitative evidence still hold if we control for other explanatory variables, we perform a logistic regression covering the 1950–2018 period for 79 countries and exploring the variables linked to the mechanisms, explained in Sections 2 and 3. Our primary dependent variable is the year of the grid connection of the reactor, which we consider to mark the establishment of the nuclear technology sector. In the Appendix, we include a sensitivity analysis with start year of the first reactor construction as the dependent variable. When presenting our results, we use regression coefficient plots [96], which display the regression coefficient as a dot and ranges of 90 % confidence intervals. If the confidence interval does not contain the zero value (marked by the red line), the results are statistically significant at the 10 % statistical significance level. A regression coefficient plot is an effective tool for summarizing the results and has the advantage of additionally showing the uncertainty of estimations (wide confidence intervals indicate a large range of uncertainty). At the same time, in our visualizations we indicate the odds ratios (see Section 3.4) and the statistical significance levels of the key results as well as the standard errors (see Appendix Tables A3–A7 for more sensitivity analyses and for results in table format).

Fig. 5A displays the results of bivariate analyses. It serves a diagnostic purpose; and it shows the plausibility of operationalization of the hypotheses through the proposed variables by indicating the direction of effect. Fig. 5B shows correlations between key variables, in particular that OECD members have higher incomes (0.35), larger economies (0.27), higher levels of democracy (0.63), and are more aligned with the USA (0.34), compared with non-OECD countries. The strong correlations between many key variables and the OECD suggest that there are not only theoretical, but also methodological, reasons to explore the

[3] Finland represents a special case, where the first reactor was supplied by the Soviet Union with safety and control equipment provided by Siemens (Germany) and Westinghouse (the US). A Swedish-supplied reactor was constructed in parallel and connected one year later.

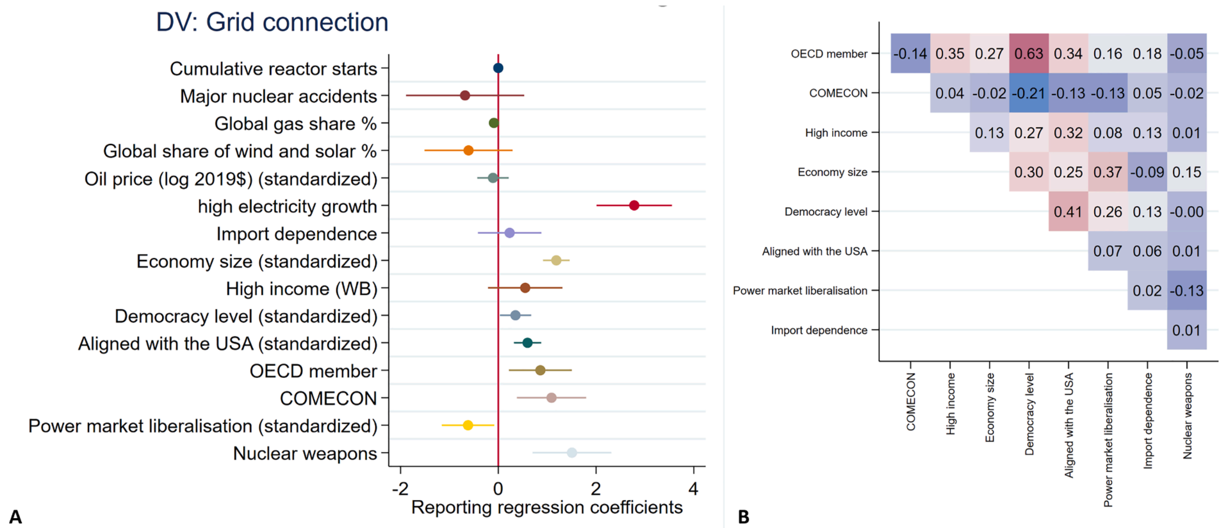

Fig. 5. Bivariate analysis of key variables and a correlation plot of context level variables *Note*: Panel A displays the regression coefficients from bivariate models for the key variables identified in Sections 2 and 3. If the confidence interval does not contain the zero value (marked by the red line), the results are statistically significant at the 10 % statistical significance level. Panel B shows simple correlations of the key context variables in a form of a heat plot [98], where darker red colors indicate stronger positive correlations and darker blue colors denote stronger negative correlations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

effects of OECD membership in a separate model. Here, we try to limit the number of binary variables that could possibly strongly overlap and we decrease the overall number of variables explored in a single model so as to avoid model overfitting [97].

For those reasons, we focus on two key model specifications when presenting our main results: one showing the combination of technological variables and OECD versus COMECON membership (Fig. 6A), and one showing the combination of technological variables and key socio-economic and geo-political characteristics, as well as controls for key policy measures (Fig. 6B).

Fig. 6A is an additional confirmation of the trends that we have observed through the qualitative exploration in Section 4.1. The odds of countries becoming nuclear are over four times higher for OECD and COMECON members than for other countries, when controlling for key technological characteristics. Among the key technological characteristics we find in the Fig. 6A specification that countries pursuing nuclear weapons are five times more likely to introduce nuclear energy than countries not pursuing nuclear weapons; we also find a minor effect of increased oil prices in the model, which includes time effects. Nuclear weapons and oil price variables are, however, not statistically significant if we focus on a range of more granular socioeconomic characteristics rather than on country categorization into OECD and COMECON. One possible explanation for the nuclear weapons variable not being statistically significant in the models displayed in Fig. 6B is that this variable correlates with the size of the economy. It is plausible to assume that it is the size of the economy that drives both the pursuit of nuclear weapons and the establishment of nuclear power.

Among the context-level characteristics, a major growth in electricity demand (over 2 TWh in the preceding 5 years) increases the odds of a state becoming nuclear more than tenfold. As we also show in the Appendix, this is, in fact, one of the most robust predictors under various model specifications (see Tables A3–A7). Another key driver is the availability of domestic fossil fuels. High import dependence increases the odds of introducing nuclear energy threefold, while as we show in Fig. 4, and in the additional specifications in the Appendix, being a major fossil fuel exporter makes the introduction of nuclear energy

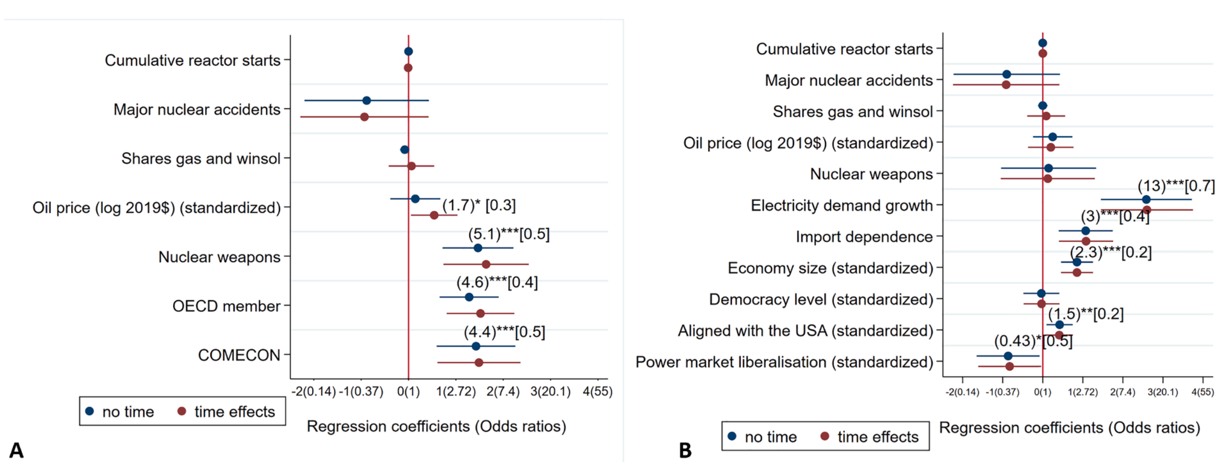

Fig. 6. Main results technology versus context characteristics *Note*: Each panel displays the regression coefficients as well as the odds ratios in parentheses. Standard Errors are indicated in the squared brackets. We always report two different specifications one with standard errors clustered by country but excluding time effects (blue) and one including time effects (red). We also present the results of these models and more combinations of different specifications in the Appendix in Table A3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

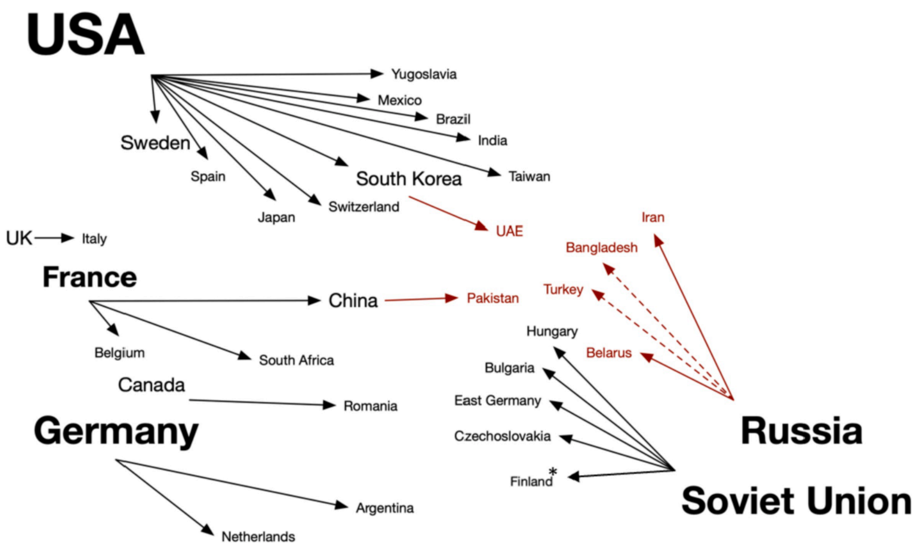

Fig. 7. Suppliers of the first (sizable) commercial nuclear reactors that led to completion of the formative phase 1950–2023. In the first period (before 1990) countries are depicted in black, in the second period (after 1990) in red. Dashed lines indicate planned but uncompleted nuclear power plants. *Notes:* Data on nuclear suppliers are from the IAEA country nuclear profiles (IAEA 2019). For current projects (displayed with a red dotted arrow) data was taken from the WNA reports (WNA 2020). *Finland represents a special case, where the first reactor was supplied by the Soviet Union but additional equipment and engineering was supplied by Western companies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

unlikely. The size of the economy is another key and extremely robust predictor of nuclear power introduction traced by many previous studies. Larger countries (increasing log GDP by 1 standard deviation), are twice as likely to introduce nuclear energy. The alignment with the USA (measured as an overlap in foreign policies) might increase the odds by 50%, suggesting the importance of being aligned with a key supplier but also of a stable foreign policy, given the dual use nature of nuclear technology. At the same time, the increasing liberalization of the power market makes the introduction of nuclear energy less likely decreasing the odds by 50%.

5. Discussion

Nuclear power adoption, similarly to the diffusion of other technologies, has been driven by socio-technical, techno-economic, and political mechanisms [33]. The main socio-technical mechanism, technology diffusion from core to periphery, has shaped the broad-brushed pattern of this transition, while the economic and political context has defined the speed and depth of the diffusion. The main conclusion of our analysis is that it was primarily the contextual factors rather than the inherent characteristics of nuclear power technology that stalled its diffusion to more countries.

Seminal literature identifies the proximity to early adopters as a defining factor shaping the spatial diffusion of new technologies [32,60]. Our analysis shows that it was not only geographic, but also the 'geopolitical' proximity that determined the diffusion of nuclear power from its initial core in the USA, UK and the USSR to other countries. This factor can be so well documented for nuclear power precisely because there were two independent 'core' regions for nuclear power: COMECON and the USA and its allies. Western industrialized suppliers supplied primarily to OECD and G20 countries (including communist China), whereas the USSR supplied primarily to its COMECON allies (see Figs. 3 and 7). The diffusion to smaller and less technologically advanced COMECON countries can mainly be explained by their geopolitical affinity to the USSR. However, even in this case, geographic proximity and economic development played an important role: nuclear power never diffused to COMECON members outside of Europe (the plans to develop nuclear power in Vietnam and Cuba were not successful). The fact that geopolitical connections were not fully decisive is also clear from the observation that some developing economies for example, Argentina, Brazil, South Africa, India and China introduced nuclear power without being strongly linked to either the USSR or the USA.

Our results on the importance of international relations for nuclear power are in line with other studies [27,61,63]. By focusing on the initial timing of nuclear power introduction we show that this factor may be one explanation of the stalling of nuclear diffusion following the end of the Cold War in the 1990s.

Besides international relations, the contextual factors that shaped the diffusion of nuclear power included national motivation and capacities [30], which can be viewed as aspects of market attractiveness that accelerate or delay technology diffusion [32]. National motivation explains why nuclear power was introduced in countries with high electricity demand growth that were dependent on imported fuels for electricity production. Domestic capacities needed for the construction of the first nuclear power plant explain why the initial introduction of nuclear power was in wealthy industrialized OECD countries and the world's largest economies.

It is generally agreed that nuclear technology is more politicized than other technologies, given its dual-use nature [61]. Yet in contrast to Neumann et al. [37], we find a statistically significant relationship, not between the political regime type and the nuclear technology onset, but rather between political ties with the main suppliers. There are several possible explanations as to why these results differ from those of Neumann et al. [37]. That study uses a comparable dependent variable (i.e., a country being in the process of construction of a nuclear power plant in a given year) and shows that non-democracies are more likely to introduce nuclear power. One variable that Neumann et al. [37] do not control for is COMECON membership, which drove the introduction of nuclear power in East European non-democracies through the diffusion from the USSR. The second variable not controlled for in their analysis is the wave of democratization in the world, which unfolded in parallel with the saturation of the nuclear markets depicted in Fig. 4 (Section 4.1). Thus, while it cannot be ruled out that democracy has an effect on the introduction of nuclear power, the results of Neuman's et al. [37] may simply reflect the parallel, but unrelated developments of nuclear market saturation and growing democratization.

We also show that the technology characteristics: the experience of the global nuclear power industry, the advances made by the main competitors (natural gas and new renewables), accidents at nuclear power plants, and the association of nuclear power with nuclear weapons did not affect the worldwide diffusion of nuclear power as much as contextual factors. The association with nuclear weapons is widely commented on in the literature and closely entangled with geopolitical factors affecting international cooperation, which as we show, has been critical for the spread of civil nuclear power. The initial technological core of civil nuclear power included the countries that possessed nuclear weapons developed during or in the immediate aftermath of World War II; this shows the well documented connection between early nuclear weapons programs and nuclear power technologies. It also explains why the less technologically advanced Soviet Union adopted nuclear power earlier than the more technologically advanced Germany and Italy. Besides this obvious connection, the pursuit of nuclear weapons, when controlled for other key contextual variables, was not a statistically significant factor in the formation of civil nuclear power regimes. Our results are different from Neumann et al. [37] because we controlled for the size of the economy (GDP), which increases the likelihood of countries having a nuclear weapon and civil nuclear power. The largest economies - USA, USSR, UK, France and later China and India - sought superpower status through nuclear weapon acquisition and at the same time had the most suitable markets and capacities for civil nuclear power. This does not negate the connection documented in case studies linking military and civil nuclear power research [21], but it stresses the obvious: the pursuit of nuclear technology for power generation was neither a pre-condition nor a necessary consequence of the nuclear weapons programs as, for example, illustrated by Italy, Germany, Japan and Canada. At the same time, we agree with Neumann et al. [37] that countries with nuclear weapons might have an incentive to also continue to sustain their civil nuclear energy program.

6. Conclusions

Our analysis advances understanding of the role of technology factors vs. context-specific factors in the global diffusion of market-anchored and policy-driven complex energy technologies. We show that at the formative phase of nuclear power, context-specific factors such as market attractiveness and ease of diffusion, played a more prominent role than technology characteristics, such as accumulated global experience, major accidents, association with nuclear weapons, and the advances made by competitors. Our paper contributes to the literature in that it draws lessons from historical studies of technology diffusion to inform the feasibility of future energy scenarios [3,4].

The main lesson of our analysis is that the suitability of technologies for climate mitigation cannot be determined by only analyzing technology characteristics in isolation from their historical and future context. Moreover, our study focuses on different characteristics of the context at both international and national levels, some unchangeable, some dynamic, and some susceptible to intervention.

The first group includes immutable country characteristics such as the size of the economy, the income level, electricity demand growth, and dependence on imported fuels. These cannot easily be changed by policy interventions, but some can evolve over time. For example, in the future the number of sufficiently large and growing economies may increase, enabling the introduction of nuclear power. The second group includes state policies. Adoption of nuclear power, like any other major energy technology, requires state involvement ranging from appropriate legislation and regulation to financial support [99]. For example, broader energy policy such as liberalization of electricity markets has a negative effect on the introduction of nuclear technology. Our study indicates that to enable the uptake of capital-intensive market-anchored technologies like nuclear power (e.g., carbon capture and storage [CCS]), liberalized electricity markets should, to some degree, be supported by additional policies to protect investors [100]. The third group of factors encompasses international cooperation. Very few countries were able to build their first nuclear reactor on their own and that may also be the case for other complex and expensive energy technologies. In the same way as COMECON and the corresponding cooperation between the USA and its allies enabled the introduction of nuclear power in almost every suitable market in the 1960s-1980s, similarly strong international cooperation might be needed for the global energy transition of the 21st century.

Our study has several limitations. Though we seek to conceptually separate technology-specific from context-specific factors, in reality there is a strong interplay between the two. For example, declining electricity demand in the core market (a contextual factor) may have weakened the global nuclear industry (a technology factor), thus reducing its ability to invest in new markets, and this, in turn, slowed down innovation in the sector. Second, in common with many studies that include quantitative analysis, ours does not fully capture variables that are difficult to consistently observe across many countries over a long time period. For example, the expectation of a stronger role for renewables may have played a role in energy planning already in the 1980s, long before wind and solar power started to generate notable shares of electricity. For the same reason, we were unable to explore the role of ideological factors that might have provided additional explanations as to why some countries with sufficient capacity did not introduce nuclear energy. The final limitation is that we focus only on the introduction of the first reactor. However, it is also important to understand what shaped the subsequent growth, stagnation, or decline of national nuclear power sectors, including the reasons why various countries took decisions to discontinue nuclear power, sometimes, as in case of Austria, even before their first newly built reactor was connected.

Despite these limitations, our study exemplifies how theories of spatial technology diffusion and technology life-cycle, particularly with respect to the formative phase of new energy technologies, can be combined with economic and political theories to understand worldwide patterns of technology adoption. This kind of research into technology adoption in a heterogenous world should be extended beyond nuclear power, in particular to more ‘granular’ [14] and ‘footloose’ [43] technologies, to advance understanding of the feasibility of various climate mitigation pathways.

Declaration of Competing Interest

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

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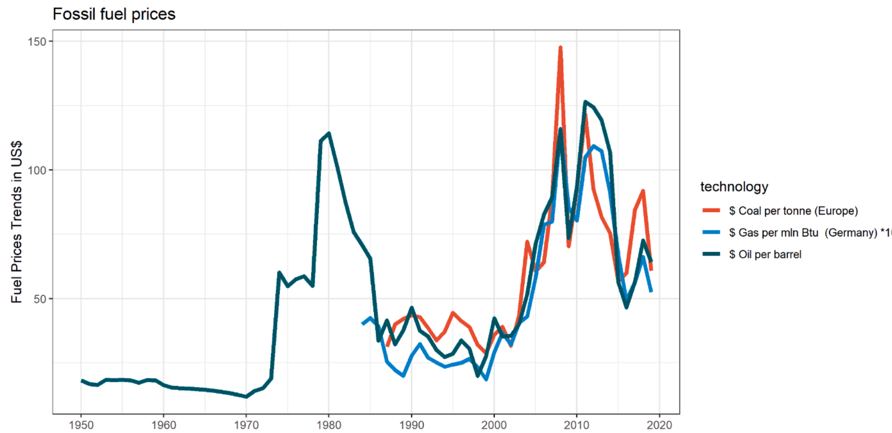
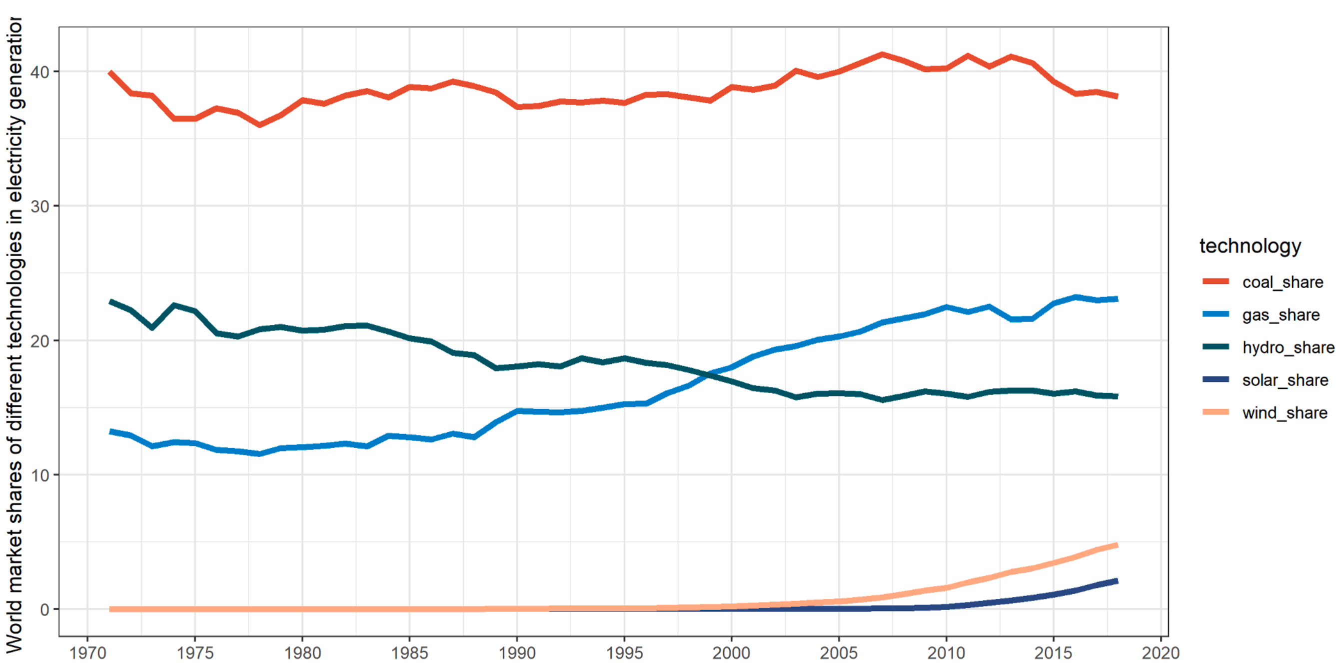
Appendix A



Source: Data is based on BP Statistical Review of World Energy June 2020: http://www.bp.com/statisticalreview

Fig. A1. Historical fossil fuel price trends Note: Fig. A1 demonstrates that coal and gas prices follow similar trends as oil prices for available historical data. Source: Data is based on BP Statistical Review of World Energy June 2020: http://www.bp.com/statisticalreview.



Source: IEA (2017). *World energy balances*, IEA World Energy Statistics and Balances (database), https://doi.org/10.1787/data-00512-en

Fig. A2. Historical technology shares in electricity generation Note: Fig. A2 shows the growth of gas shares in electricity generation post 1995 and the uptake of renewables around 2005. Source: IEA (2017). *World energy balances*, IEA World Energy Statistics and Balances (database), https://doi.org/10.1787/data-00512-en.

Table A1
Years of the first and second NPP grid connection and the proposed take-off year. Table A1 displays the information about the first two reactors that were used to select the reactor that marks the "take-off" or the accomplishment of the formative phase of nuclear technology. In our additional analyses we also included the year of construction start for the year which we consider to mark the take-off.

Country	Year (capacity)		Take-off year (grid connection)	Take-off year (construction start)
	First NPP	Second NPP		
UK	1956 (49 MW)	1957 (49 MW)	1956	1953
US	1957 (24 MW)	1957 (60 MW)	1957	1956
France	1959 (39 MW)	1960 (40 MW)	1959	1955
Italy	1964 (303 MW)	1965 (260 MW)	1964	1959
Soviet Union	1954 (5 MW)	1964 (299 MW)	1964	1957
West Germany	1962 (15 MW)	1966 (114 MW)	1966	1960
East Germany	1966 (62 MW)	1974 (408 MW)	1966	1960
Japan	1965 (12 MW)	1966 (137 MW)	1966	1961
Canada	1962 (22 MW)	1968 (206 MW)	1968	1960
India	1969 (300 MW)	1973 (90 MW)	1969	1964
Spain	1969 (141 MW)	1971 (446 MW)	1969	1964
Switzerland	1969 (365 MW)	1972 (365 MW)	1969	1965
Sweden	1964 (10 MW)	1972 (473 MW)	1972	1966
Netherlands	1969 (55 MW)	1973 (482 MW)	1973	1969
Argentina	1974 (340 MW)	1984 (600 MW)	1974	1968
Bulgaria	1974 (408 MW)	1975 (408 MW)	1974	1970
Belgium	1962 (10 MW)	1975 (1828 MW)	1975	1970
Finland	1977 (507 MW)	1978 (880 MW)	1977	1971
South Korea	1978 (576 MW)	1983 (661 MW)	1978	1972
Taiwan	1981 (1208 MW)	1982 (1902 MW)	1981	1975
Czechoslovakia	1972 (93 MW)	1980 (408 MW)	1980	1972
Hungary	1983 (470 MW)	1984 (473 MW)	1983	1974
Yugoslavia	1983 (688 MW)		1983	1975
South Africa	1984 (930 MW)	1985 (930 MW)	1984	1976
Brazil	1985 (626 MW)	2001 (1275 MW)	1985	1971
Mexico	1990 (777 MW)	1995 (775 MW)	1990	1976
China	1994 (2186 MW)	2002 (2237 MW)	1994	1987
Romania	1996 (650 MW)	2007 (650 MW)	1996	1982
Pakistan	1972 (90 MW)	2000 (300 MW)	2000	1993
Iran	2013 (915 MW)		2013	1975
Projected take-off				
Belarus	2020 (1110 MW)	2020 (1110 MW)	2020	2013
UAE	2020 (5380 MW)	2020 (1345 MW)	2020	2012
Bangladesh	2023 (1200 MW)	2024 (1200 MW)	2023	2017
Turkey	2023 (1200 MW)	2024 (1200 MW)	2023	2018

Source: IAEA country profiles and WNA country reports (IAEA 2019; WNA, 2020).

Table A2
Sample overview 1950–2018 Table A2 provides an overview of countries that were included in the sample and the year of when they entered the sample (many countries were created in the process of decolonization or the breakdown of the Soviet Union).

Countries which operate or have operated sizeable commercial nuclear power plants	Countries which have not operated commercial nuclear power plants
Argentina (1950), Bangladesh (1971), Belarus (1991), Belgium (1950), Brazil (1950), Bulgaria (1950), Canada (1950), Chile (1950), China (1950), Czechoslovakia (1950), France (1950), German Democratic Republic/East Germany (1954), German Federal Republic/West Germany (1950), Hungary (1950), India (1950), Iran (1950), Italy (1950), Japan (1950), Mexico (1950), Netherlands (1950), Pakistan (1950), Romania (1950), South Africa (1950), South Korea (1950), Soviet Union (1950), Spain (1950), Sweden (1950), Switzerland (1950), Taiwan (1950), Turkey (1950), United Arab Emirates (1971), United Kingdom (1950), United States (1950), Yugoslavia (1950)	Algeria (1962), Australia (1950), Austria (1955), Azerbaijan (1991), Bahrain (1971), Cuba (1950), Denmark (1950), Ecuador (1950), Egypt (1950), Finland (1950), Georgia (1991), Ghana (1957), Greece (1950), Indonesia (1950), Ireland (1950), Israel (1950), Jordan (1950), Kazakhstan (1991), Kuwait (1961), Laos (1953), Libya (1951), Malaysia (1957), Morocco (1956), Myanmar (1950), New Zealand (1950), Nigeria (1960), North Korea (1950), Norway (1950), Oman (1971), Paraguay (1950), Peru (1950), Philippines (1950), Poland (1950), Portugal (1950), Qatar (1971), Saudi Arabia (1950), Singapore (1965), Sri Lanka (1950), Sudan (1956), Syria (1950), Thailand (1950), Tunisia (1956), Uzbekistan (1991), Venezuela (1950), Vietnam (1954)

Table A3
Reporting the results from Fig. 6 and additional specifications. Note: Table A3 shows the results that are reported in Fig. 6A – Model (1) and Fig. 6B – Model (2) with time trends. Model (3) additionally includes “High income” and a binary measure of the breakdown of the USSR. Model (4) includes the variable “oil exporter” instead of “import dependence”. Model (5) looks at the possible effect of the variable “state failure” instead of the variable “democracy”.

DV: grid connection	(1)	(2)	(3)	(4)	(5)
Cumulative reactor starts	−0.00844 (0.00827)	0.000815 (0.00926)	−0.00505 (0.00984)	−0.00487 (0.00983)	−0.00738 (0.00986)
Major nuclear accidents	−0.931 (0.823)	−0.914 (0.807)	−1.007 (0.809)	−1.021 (0.807)	−1.015 (0.816)
Shares gas and winsol	0.0621 (0.292)	0.0855 (0.287)	−0.0807 (0.304)	−0.115 (0.307)	−0.160 (0.304)
Oil price (log 2019$)	0.542* (0.299)	0.200 (0.345)	0.153 (0.346)	0.176 (0.331)	0.134 (0.344)
Nuclear weapons	1.638*** (0.547)	0.125 (0.714)	0.108 (0.693)	−0.0668 (0.690)	0.149 (0.676)
OECD member	1.520*** (0.434)				
COMECON	1.487*** (0.533)				
Electricity demand growth		2.600*** (0.698)	2.506*** (0.649)	2.385*** (0.649)	2.069*** (0.650)
Import dependence		1.079*** (0.411)	0.986** (0.395)		
Economy size		0.854*** (0.243)	0.897*** (0.240)	0.695*** (0.219)	0.780*** (0.240)
Democracy level (standardized)		−0.0300 (0.272)	0.0672 (0.273)	0.147 (0.269)	
Aligned with the USA (standardized)		0.412** (0.207)	0.430* (0.231)	0.416* (0.239)	0.431* (0.229)
Power market liberalisation (standardized)		−0.826* (0.478)	−0.783 (0.491)	−0.789* (0.475)	−0.753* (0.456)
High income (WB)			−0.677 (0.435)	−0.693 (0.434)	−0.518 (0.423)
USSR			−1.386 (1.127)	−1.588 (1.146)	−1.737 (1.219)
Oil exporter				0 (.)	−1.518 (0.990)
State Failure (5 years)					−0.937 (0.959)
Constant	−17143.8*** (5112.0)	109.2 (367.7)	−180.9 (407.5)	−202.0 (406.7)	−290.3 (405.2)
Observations	3781	3651	3651	3141	3750
AIC	326.5	270.5	271.6	266.2	282.4

Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A4
Reporting the results from Table A3 but looking at construction start as the dependent variable Note: Table A4 shows same model specification as in A3. The major differences are highlighted in bold. The share of gas and wind + solar energy in electricity generation are now positive and statistically significant, nuclear accidents are also statistically significant and positive, while power market liberalization is more robust and statistically significant in all model specifications as compared to the specification where the year of grid connection is taken.

DV: construction start	(1)	(2)	(3)	(4)	(5)
Cumulative reactor starts	0.00211 (0.34)	0.00299 (0.44)	0.00139 (0.17)	0.00176 (0.22)	0.00261 (0.33)
Major nuclear accidents	−0.0165 (−0.02)	0.210 (0.25)	0.196 (0.24)	0.144 (0.17)	0.117 (0.14)
Shares gas and winsol	***0.578** (2.57)***	***0.485** (2.36)***	***0.452** (2.05)***	***0.447** (2.05)***	***0.466** (2.15)***
Oil price (log 2019$) (standardized)	0.410 (0.85)	0.116 (0.27)	0.140 (0.34)	0.129 (0.31)	0.105 (0.25)
Nuclear weapons	***2.838*** (6.27)***	***1.951*** (3.35)***	***1.873*** (3.14)***	***1.830*** (2.97)***	***1.988*** (3.42)***
OECD member	1.459*** (3.38)				
COMECON	2.024*** (5.09)				
Electricity demand growth		2.213*** (4.26)	2.199*** (4.25)	2.008*** (3.87)	2.062*** (4.08)
Import dependence		1.054** (2.44)	1.010** (2.32)		
Economy size (standardized)		0.698** (2.50)	0.741*** (2.68)	0.572** (2.33)	0.608** (2.52)
Democracy level (standardized)		−0.327 (−1.50)	−0.286 (−1.28)	−0.226 (−0.97)	
Aligned with the USA (standardized)		0.758*** (3.11)	0.779*** (3.10)	0.750*** (3.03)	0.562** (2.40)
Power market liberalisation (standardized)		***−0.820*** (−3.22)***	***−0.808*** (−2.84)***	***−0.749*** (−2.71)***	***−0.751** (−2.54)***
High income (WB)			−0.454 (−0.85)	−0.522 (−1.03)	−0.354 (−0.76)
USSR			−0.537 (−0.35)	−0.794 (−0.50)	−0.846 (−0.55)
Oil exporter				−1.120 (−1.02)	−0.579 (−0.78)
State failure (5 years)					0.462 (0.82)
Constant	−10001.5*** (−3.22)	347.0 (1.31)	274.4 (0.84)	270.2 (0.84)	299.0 (0.95)
Observations	3549	3427	3427	3427	3519
AIC	327.6	288.3	291.4	294.3	301.5

t statistics in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A5
Reporting the results from Table A3 but using a specification with Cox regression. Note: Table A5 shows similar model specification as in A3 but using a Cox regression. The major differences are highlighted in bold. In Model (2) both foreign policy and liberalization variables become statistically insignificant, while the direction of the effect is the same. Other main results are similar. * Indicates when a variable violates proportional hazard assumption.

DV: Grid connection	(1) Analysis time when record ends	(2) Analysis time when record ends
Major nuclear accidents	28.90*** (24.44)	27.70 (0.00)
Shares gas and winsol	−0.655*** (−3.15)	−1.074 (−0.62)
Oil price (log 2019$) (standardized)	−0.788*** (−3.67)	−1.322 (−0.34)
Nuclear weapons	1.637*** (3.34)	0.0689 (0.12)
OECD member*	1.527*** (3.78)	
COMECON	1.561*** (3.06)	
Electricity demand growth		2.364*** (4.00)
Import dependence		1.013** (2.17)
Economy size (standardized)		0.832** (2.55)
Democracy level (standardized)		0.114 (0.49)
Aligned with the USA (standardized)		**0.205 (0.71)**
Power market liberalisation (standardized)		**−0.329 (−0.59)**
Observations	3781	3651
AIC	236.0	181.2

Table A6
Reporting the results for different specifications of nuclear accidents – grid connection. Note: In Table A5, we present the results from the specifications where we focus on nuclear accidents and include three major nuclear accidents separately (Chernobyl, TMI and Fukushima) and also code 2 years after as a positive outcome. We also tried specifications where we coded additional 7 years as a positive outcome but with these specifications the models were not converging. Adding a different operationalization of nuclear accidents does not change our key results but it shows that Chernobyl had globally a negative effect.

DV: Grid connection	(1)	(2)
Cumulative reactor starts	−0.00819 (−0.91)	0.00395 (0.40)
Shares gas and winsol	−0.0711 (−0.23)	0.0692 (0.22)
Oil price (log 2019$) (standardized)	0.312 (0.90)	−0.0618 (−0.16)
Nuclear weapons	1.649*** (3.01)	0.134 (0.19)
OECD member	1.533*** (3.53)	
COMECON	1.501*** (2.83)	
Chernobyl	***0 (.)***	***0 (.)***
TMI	−1.245 (−1.13)	−1.042 (−0.91)
Fukushima	2.847* (1.93)	1.640 (1.31)
Electricity demand growth		2.629*** (3.70)
Import dependence		1.081*** (2.62)
Economy size (standardized)		0.857*** (3.52)
Democracy level (standardized)		−0.0428 (−0.16)
Aligned with the USA (standardized)		0.412** (1.99)
Power market liberalisation (standardized)		−0.813 (−1.63)
Constant	−19029.8*** (−3.63)	189.3 (0.48)
Observations	3634	3507
AIC	325.6	268.9

t statistics in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A7
Reporting the results for different specifications of nuclear accidents – construction start. Note: In Table A6, we present the results from the same specifications as in Table A5 but take the construction start as the dependent variable. The main results still hold but in this specification, we detect a negative effect of TMI.

DV: construction start	(1)	(2)
Cumulative reactor starts	0.00434 (0.70)	0.00731 (1.04)
Chernobyl	0.921 (0.70)	0.544 (0.42)
TMI	**0 (.)**	**0 (.)**
Fukushima	1.028 (0.97)	1.420 (1.35)
Shares gas and winsol	0.689** (2.53)	0.589** (2.49)
Oil price (log 2019$) (standardized)	0.664 (1.22)	0.188 (0.39)
Nuclear weapons	2.849*** (6.09)	1.996*** (3.39)
OECD member	1.488*** (3.41)	
COMECON	2.085*** (5.09)	
Electricity demand growth		2.248*** (4.41)
Import dependence		1.032** (2.39)
Economy size (standardized)		0.698** (2.40)
Democracy level (standardized)		−0.343 (−1.58)
Aligned with the USA (standardized)		0.780*** (3.00)
Power market liberalisation (standardized)		−0.849*** (−3.26)
Constant	−11507.4*** (−3.57)	526.3* (1.87)
Observations	3408	3289
AIC	323.4	284.9

t statistics in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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