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Destined for decline? Examining nuclear energy from a technological innovation systems perspective

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ABSTRACT

Technology decline is a central element of sustainability transitions. However, transition scholars have only just begun to analyze decline. This paper uses the technological innovation systems (TIS) perspective to study decline. Our case is nuclear energy, which is at a crossroads. Some view nuclear as a key technology to address climate change, while others see an industry in decline. We examine a broad range of empirical indicators at the global scale to assess whether or not nuclear energy is in decline. We find that an eroding actor base, shrinking opportunities in liberalized electricity markets, the break-up of existing networks, loss of legitimacy, increasing cost and time overruns, and abandoned projects are clear indications of decline. Also, increasingly fierce competition from natural gas, solar PV, wind, and energy-storage technologies speaks against nuclear in the electricity sector. We conclude that, while there might be a future for nuclear in state-controlled 'niches' such as Russia or China, new nuclear power plants do not seem likely to become a core element in the struggle against climate change. Our conceptual contribution is twofold. First, we show how the TIS framework can be mobilized to study technology decline. Second, we explore a range of indicators to cover the multiple dimensions of decline, including actors, institutions, technology, and context.

1. Introduction

For many years, research in the field of sustainability transitions has focused on emerging technologies and how to support the early stages of innovation and transformation. As transitions accelerate, however, the decline of existing industries and technologies also becomes a central issue [1,2]. Decline may be a consequence of ongoing substitution processes [3], but it may also be the outcome of deliberate policy decisions [4,5]. It is important to improve our understanding of decline—for example, so we can potentially accelerate the phase-out of unsustainable technologies, or mitigate unwanted negative effects during decline [6].

The destabilization and decline of established socio-technical systems are still relatively new topics in transition studies [7]. Existing studies have so far looked at selected industries (e.g., coal, or pulp and paper) at the regional or national level [2,8-10]. The literature on industry dynamics, meanwhile, has primarily studied the decline of specific industries in specific regions [11].

In this paper, we study technology decline at the global scale. This means that we look at global developments, statistics, and indicators.[1] Such a perspective is important for global sustainability challenges such as climate change, in which local developments play a role but it is the global aggregate that matters in the end. To phase out CO_2-intensive technologies such as coal-fired power generation, it will be important to track and understand developments at a global scale. The same argument applies to the (global) diffusion of clean technologies.

The question we pose is whether or not nuclear power is in a phase of global decline. If the answer is yes, this will limit the range of technology options that remain available at a large scale to combat climate change. In general, the global decline of a technology involves losing not only 'core firms', but also suppliers, customers, networks, skilled labor, regulatory support, legitimacy, and other complementary

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[1] Note that we do not use the "global innovation systems" perspective [105], which suggests tracking innovation processes across multiple scales (local, regional, national, international). Instead, and as a first step, we concentrate on global indicators. Expanding our analysis to include multi-scalar interactions would certainly be an interesting avenue for future research.

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resources in critical parts of international value chains. This means that, at some point, a vicious circle of adverse developments might kick in and seal a technology's fate.

Our study focuses on nuclear energy for commercial power generation in large, civil reactors. This technology is at a crossroads. Some believe it will enjoy a renaissance, driven by new constructions in Asia and the increasing urgency to mitigate climate change [12]. Others see nuclear as an industry in decline, whose operating capacity has stagnated for more than two decades and that has failed to reduce costs and address concerns over public acceptance, safety, nuclear waste, and proliferation [13-15].

This paper is rooted in the field of sustainability transitions [7]. Our theoretical basis is the technological innovation systems (TIS) framework [16]. We build on a recent conception of a TIS's lifecycle [17]. The TIS framework allows us to focus on a selected technology (instead of an entire socio-technical system), while maintaining a multi-dimensional, systemic perspective that encompasses organizational, institutional, technological, and contextual developments.

Conceptually, our paper seeks to improve the way scholars analyze technology decline. We gather experiences through different indicators, and provide first insights into the underlying processes of decline. With our data we seek to cover the entire life of the nuclear industry from its origins in the 1950s to the present day, even though our primary interest is in the current stage of development. We look at a broad array of statistics, papers, and reports to arrive at a comprehensive, multi-dimensional assessment.

Next, we introduce our theoretical background (Section 2) and nuclear technology (Section 3). This is followed by our methods (Section 4) and results (Section 5), where we answer our central question. In the discussion section (Section 6), we revisit the conceptual implications of our study. Section 7 concludes.

2. Theoretical background

2.1. Transition studies and decline

Sustainability transitions represent a rapidly growing field of research in innovation studies [18]. Sustainability transitions are fundamental changes in sectors such as energy, transportation, food, or water towards more sustainable modes of production and consumption [19]. The ongoing transition of the electricity sector towards increasing shares of renewable energies such as wind and solar-PV can be viewed as an example of a sustainability transition [1, 20].

The decline of technologies, together with their associated industries[2], is an essential process of sustainability transitions. As some transitions have reached a new stage of development, in which alternatives have diffused to a degree that threatens established technologies, decline has received increasing attention lately [2, 4, 21]. However, technology decline is still a relatively understudied topic in transitions research [7].

There are several reasons to improve our understanding of decline. One is to accelerate decline in order to reduce the impacts of unsustainable technologies as quickly as possible [4]. Another is to cope with the negative consequences of decline, such as job losses or the strong opposition of incumbent actors, thereby reducing resistance to change [6, 22]. A third reason is to understand the interplay of emerging and declining technologies. This is particularly relevant for sectors such as electricity, where the complementary interaction of new and old technologies (e.g., how to complement variable renewables) is key for the performance of the entire sector [23].

Fourth, from a conceptual perspective, it is important to identify key processes in the decline of technologies—e.g., to compare with those that characterize the emergence of innovation. Some processes may be similar, such as the intensification of knowledge generation due to mounting pressure from newer, rival technologies (the sailing ship effect); some may be inverted, such as formation vs. loss of legitimacy or entry vs. exit of firms; and others may simply be different, such as pushback against decline by incumbent businesses and other vested interests.

Another interesting aspect of (global) decline is the associated loss of technology diversity. Diversity is a key issue, as it determines the range of possible transition pathways [24]. In the past, many technologies (e.g., steam power) have declined and are hardly missed today. In some cases, such as vinyl records, technologies have declined, yet have since been rediscovered and revived in the present day. In principle, it is possible to revive an “extinct” technology (if it is needed at a later point in time), because the required knowledge typically still exists. Nonetheless, such a revival may be both challenging and time-consuming, once the underlying TIS—including organizational competences, educational programs, skilled workers, value chains, legitimacy, and regulatory support—is gone. So, there may be an argument for keeping a technology alive solely in order to maintain diversity.

2.2. Technological innovation systems and decline

In order to study decline in the case of nuclear, we build on the technological innovation systems (TIS) approach (see, e.g., [16] or [25] for an overview). This perspective highlights the systemic interplay of actors and institutions in a specific technological field, as well as the importance of system resources and interactions with broader contextual structures [26, 27].

In transition studies, the TIS has typically been used to study the emergence of new technologies, thereby focusing on processes, or functions, to support the development, diffusion, and use of the focal technology [16, 28]. More recently, scholars have also begun to look into the decline of TISs [4]. One conceptual suggestion is to view the TIS as a configuration that changes over time and may pass through different lifecycle stages, including *formation, growth, maturity,* and *decline* [17]. We build on this to examine decline, and we also use the four analytical dimensions suggested: (i) actor base and TIS size; (ii) institutional structure and networks; (iii) technology performance and variety; and (iv) TIS-context relationships (cf. Table 1).

To study decline, it is also important to acknowledge that the focal TIS is embedded in a wider context (Fig. 1), which includes complementary and competing technologies but also wider macroeconomic, political, and societal systems and developments [26]. As these contextual elements change (often independently of event within the TIS), they may have a substantial impact on the focal technology. In fact, technology decline is often triggered or exacerbated by contextual changes.

This brings us to the causes of decline. External causes include disruptive events such as the economic crisis of 2008, or the disaster at the Fukushima nuclear plant in 2011, as well as changes in macroeconomic conditions such as fluctuations in the prices for critical commodities (e.g., oil or gas). Another cause may be changing regulatory environments, as in the case of energy market liberalization in the 1990s [29] or bans or phase-out policies [10]. Equally disruptive can be changes in competing and complementary technologies [30]: if critical inputs or technology components become cheaper (or, conversely, scarcer and more expensive) or if major competing technologies improve rapidly, this has major effects on the focal technology [31].

However, decline can also be caused by problems originating in the focal TIS. Negative externalities or increasing resource needs by the focal technology may lead to a major misalignment with, e.g., societal

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[2] Note that we use “technology decline,” “industry decline” and “TIS decline” interchangeably. What we mean is that we focus on a specific technology, but include wider industry dynamics such as the entries and exits of firms, regulatory changes, or reconfigurations of inter-firm networks. Conceptually, we use the technological innovation systems (TIS) perspective to analyze these changes.

Table 1
Indicators and indicative questions to identify TIS decline (based on [17]).

	Decline phase	Indicative questions
Actor base and TIS size	Dominant players and intermediary actors lose influence; high exit rates; market decline; conflicts	Has the actor base weakened? Are key players exiting? Is the market in decline?
Institutional structure and networks	Decline of regulatory support; norms /designs questioned; value chains and networks break up; weak expectations	Is political support eroding? Do actor networks break up? Do expectations deteriorate?
Technology performance and variety	Performance may improve further (sailing ship effect); key performance parameters /designs questioned	Does technology performance stagnate, decline, or improve again?
Context: TIS-context relationships	Relations break up; competing technologies gain momentum; increasing landscape pressure	Do competing technologies become stronger, while complementarities weaken?

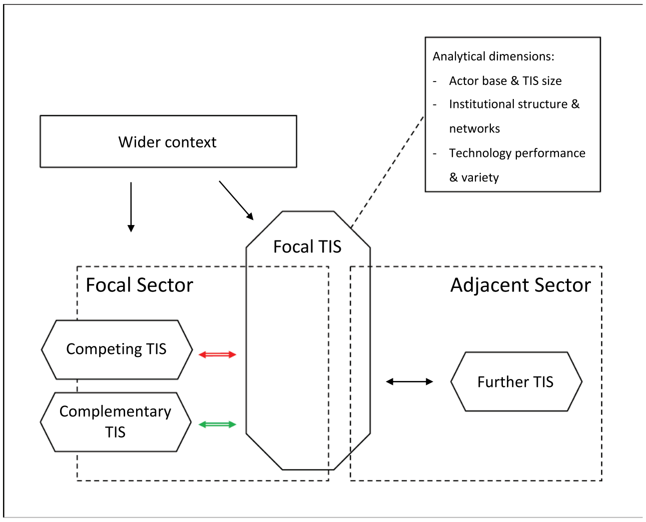

Fig. 1. Focal TIS and interactions with contextual elements.

values, thereby undermining the technology's legitimacy. This happened in the case of biomass, with spiraling demands for land and energy production in competition with food production [32]. Another example was urban air-quality degradation and attendant health issues as a consequence of emissions from coal-burning steam engines [3] or coal-fired power plants [10].

3. An introduction to nuclear energy

Nuclear energy technology and nuclear material is used for a broad range of military and civil purposes. Here we focus on the TIS for large, civil, stationary reactors for commercial power generation. These reactors are part of a much larger value chain around nuclear fuels (with key tasks such as uranium mining, enrichment, and fuel fabrication), reactors (planning, construction, operation, maintenance, decommissioning) and nuclear waste (storage, transport, processing, ultimate disposal). Within the TIS for commercial reactors we focus on the task of reactor design and construction (see Section 4 for further details).[3] For further information on the TIS context (e.g., small modular reactors) see Section 5.4.

3.1. Key characteristics

Nuclear energy can be viewed as a type of technology with the same characteristics as "complex products and systems" [33]. It is a demanding, project-based technology with very high upfront investments and long lead times—i.e., completing planning, licensing, and reactor construction can take more than 10 years [34,35]. Once they are operational, commercial nuclear power plants typically run for 40 years or more. As a consequence, there are extreme time lags.[4]

The costs of electricity from new nuclear power plants vary. In 2012, the French Cour des Comptes estimated the production cost of the new generation of EPR reactors connected to the grid in 2020 ranged between 7 and 9 €ct/kWh [36]. More recently, the British government agreed to pay more than 10 €ct/kWh for the production from the two nuclear reactors in construction at Hinkley Point.

Investment costs of nuclear plants are very high, while operational costs are comparatively low. Investments into nuclear require several decades to pay back. Consequently, nuclear investments are particularly sensitive to uncertainties in licensing and construction, and to long-term variability of electricity prices and capital costs. This increases the risks in liberalized electricity markets with intense competition and price uncertainty [37]. Competitive markets, however, could benefit nuclear if low-carbon, dispatchable generation is supported by specific policies [38].

Nuclear is a "high-tech" technology, which demands skilled labor and specific technological and organizational competences. Also, it requires the involvement of many different actors, including technology providers, specialized suppliers, power producers, regulators, policy makers, civil society organizations, financial investors, etc. Finally, nuclear depends heavily on specific policies and regulations concerning licensing, safety, monitoring, and waste handling.

In environmental terms, there are positive and negative sides to nuclear. A key issue in current debates is its carbon intensity. Some argue that, as a low-carbon energy technology, nuclear will be needed to achieve deep decarbonization in the future [12, 39]. For existing reactors, the low-carbon argument is important, especially if nuclear is replaced by fossil fuels in the short term. In California, for instance, the 2012 closure of the San Onofre nuclear power plant mainly resulted in replacement electricity being generated from natural gas [40]. In Japan, after the sudden halt at all nuclear plants following the accident in the Fukushima Daiichi plant, the share of electricity generated from fossil fuels jumped from about 60% to above 80% [41].

For new constructions, however, the situation is more complex, as it can take 10 years or more to bring new capacity online—especially in places where nuclear is contested and public participation is granted. This is considerably longer than the timescales required for other low-carbon technologies such as solar PV and wind, which can be developed in a more modular fashion. It has been argued that "climate effectiveness" (carbon, time, and costs), as opposed to carbon alone, is more relevant for strategies to address climate change [14, p. 228].

Nuclear technology also comes with many problematic aspects. These include the risk of nuclear accidents, the risk of proliferation of nuclear material, the unresolved issue of long-term and safe disposal of

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[3] We use the term "nuclear energy technology" to refer to the commercial use of nuclear for power generation, and "nuclear TIS" (or "nuclear industry") for the actors, institutions, networks, and technology involved in the specific activity of reactor construction.

[4] In the scenario of decline, this means that even if no more new reactors are built, it can be decades before the last nuclear plants are shut down—not to mention subsequent deconstruction and disposal, which again takes a long time, demanding specialised competences and significant financial resources.

highly radioactive waste, or the thermal pollution of bodies of water [42]. As these issues have been discussed elsewhere, we don't elaborate on them here.

3.2. Development and diffusion

Nuclear energy was developed in the 1950s, and numerous commercial nuclear power plants were built from the 60s to the 80s (cf. Fig. 2). A significant influencing factor on nuclear development was its relation with military purposes during the cold war [43]. Modern commercial light-water reactors, for example, follow design principles optimized for nuclear-propelled submarines, and production of weapons material played a role in reactor designs as well.

After the boom, technology diffusion stagnated. Between the 90s and the early 2000s, only a handful of new plants were connected to the grid. In recent years, however, nuclear has seen an increase of projects, led by China and South Korea. In May 2019, 31 countries operated nuclear power plants with an installed capacity of 422 GW, generating around 10% of the global power supply. The global share has declined since the mid-90s (Fig. 3). The average share in countries with nuclear power is nearly 23% [38, 44].

As the current fleet of nuclear reactors ages, many will be shut down in the coming decades. Of the 451 nuclear reactors operating in 2018, 242 had been producing commercially for 32 years or more [44]. New constructions are at much lower levels than the plants that will soon be decommissioned. For example, France, which generated 72% of its electricity from nuclear in 2018, is considering reducing this share to 50% by 2035 [47].

4. Methods and indicators

4.1. Case selection and scope

We chose to study nuclear power generation for three reasons. First,

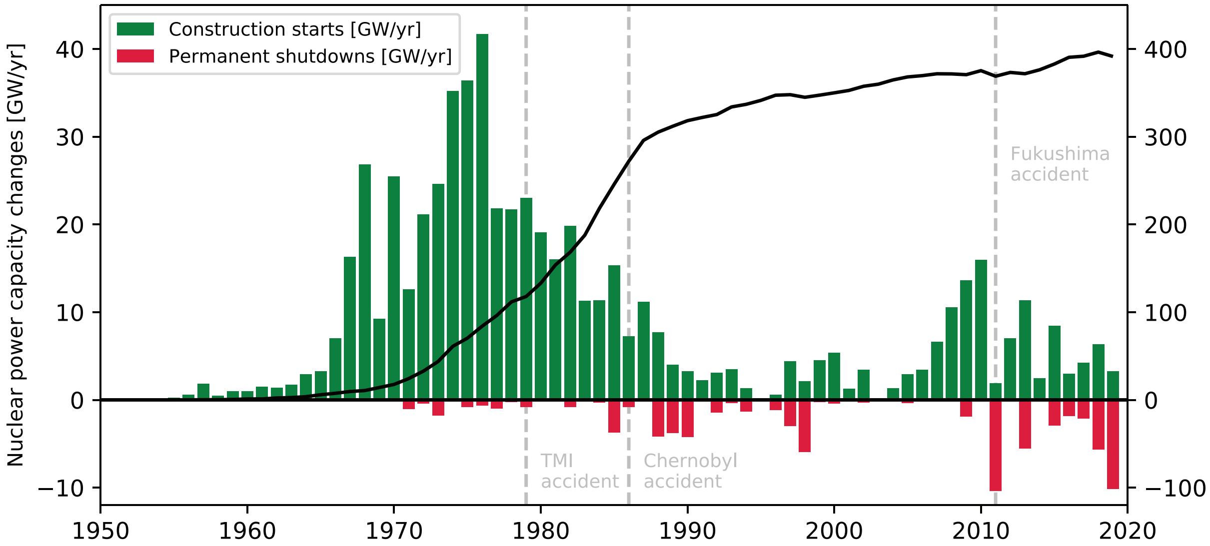

Fig. 2. Global diffusion of nuclear power generation [45]. Construction starts (grey bars), grid connection (blue line), plant shutdown (orange line), cumulative capacity (yellow line, right axis).

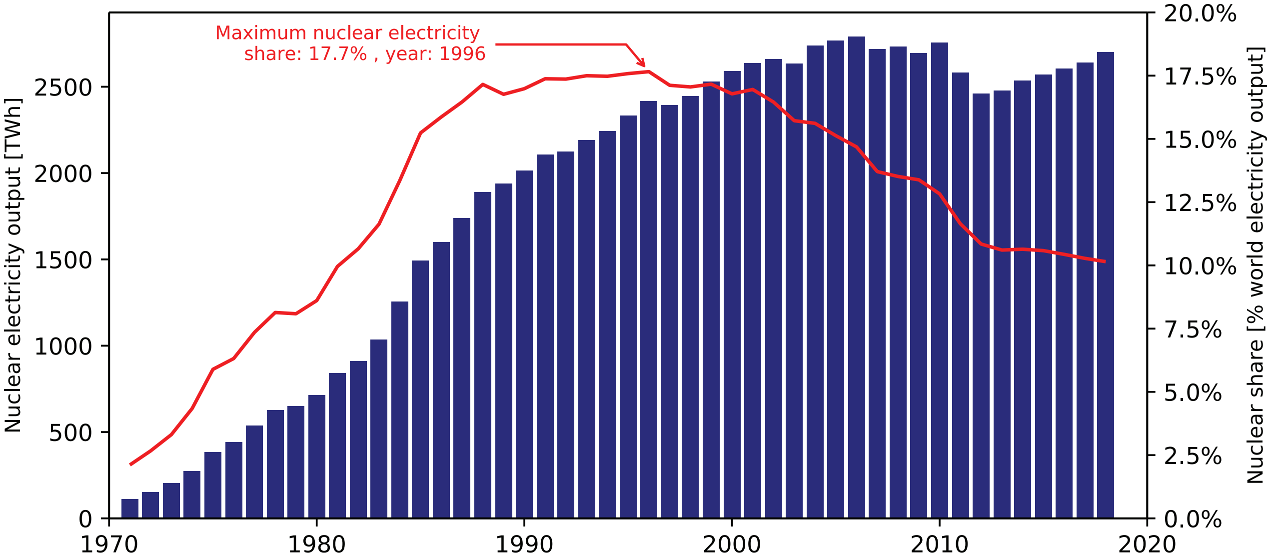

Fig. 3. Net nuclear power production (bars) and share of global electricity generation (line) from 1971 to 2018. [46].

it is a relevant energy generation technology and particularly important for climate change. Second, nuclear is a mature technology that has been in a state of stagnation for many years. It might become the first contemporary, incumbent energy-generation technology to face global decline. Third, there is a host of data and statistics, as well as a rich corpus of research and reports, available for us to use.

Our analysis targets developments at the global level. However, in some cases we had to zoom in on national or regional developments. We cover the entire life of nuclear technology, from its beginnings in the 1950s up to the present day, although our main focus is on recent developments. We concentrate on commercial, civil reactors that are currently under construction or already in operation. We acknowledge that there is innovation in terms of small modular reactors and new entrants with an interest in building them, but we don't include them in our analysis. This is due to SMRs' early stage of development (no pilot projects or prototypes) and because the effects so far on the mainstream nuclear industry seem to be very limited. We also exclude reactors designed for non-civilian purposes, such as military use.

Moreover, we focus on reactor (design and) construction, as opposed to power generation. Our reasons are as follows. First, we expect the signs of decline to manifest themselves first in the upper parts of value chains—especially for technologies with long lifetimes. Second, construction reflects the technology frontier, i.e., current technological, economic, and sociopolitical performance. Third, new construction is critical for a technology such as nuclear to survive in the long run.

4.2. Indicators and data sources

We developed a set of indicators inspired by the framework in Table 1 and related literature on industry lifecycles and technology change [54, 55]. Different measures were assigned to each of these indicators, from key actors to technology diversity and context. Data was drawn from a range of comprehensive and recognized sources (e.g., International Atomic Energy Agency (IAEA), International Energy Agency, IEA). See Table 2 for a list of indicators and sources. Note that there are clearly more indicators to be used in future studies to analyze decline—e.g., number of jobs in the focal industry or financial investments (as proxies for actor base and market size respectively). Here, we had to limit ourselves to those indicators we could retrieve at the global scale with reasonable effort. Also note that some indicators—e.g., number of jobs—might be subject to other influences, such as gains in productivity or increasing automation.

In order to conduct the network analysis in Section 5.2.2, we analyzed the data available in the International Atomic Energy Agency Power Reactor Information System (IAEA PRIS). We prepared the data by removing reactors for which there was no information on their construction and grid-connection dates (mostly canceled plans or constructions). In addition, we reduced the number of firms (i.e., nodes) by controlling for organizations that changed their names over time (e.g., KWU and Siemens, Framatome and Areva) and conglomerates or umbrella organizations (e.g., Rosatom). We used the open-source software Gephi to visualize the network.

5. Results

5.1. Actor base and TIS size

5.1.1. Actor base

The TIS for nuclear reactor design and construction is dominated by a few large incumbent firms. Since the 1960s, 11 firms have delivered over 70% of the nuclear power capacity installed worldwide [45]. Five of these are state-owned organizations, while the other six are private.

The handful of firms at the helm of the nuclear TIS has shifted over time (Fig. 4). The first wave of constructions was driven by American firms such as Westinghouse (WH), General Electric (GE), and Combustion Engineering (CE), along with French Framatome, Russian Rosatom, and German Siemens. The abrupt collapse of construction during the 1980s, however, hit North American firms particularly hard [56]. After two decades of stagnation, five of the largest reactor suppliers had merged or exited the nuclear TIS. At the same time, two new players entered the TIS, timidly at first: South-Korean KEPCO and Chinese CNNC. Table 3 shows the largest reactor suppliers by number of units.

Another wave of constructions occurred around 2010 and thereafter. It was headed by state-owned firms from Russia, France, South Korea, and China, followed by Japanese Hitachi and Toshiba. Excitement grew over a long-awaited renaissance for nuclear energy that was driven, in part, by rapidly growing electricity demand in emerging economies. However, this second wave of constructions was not only much smaller than the first, but also regressed after a decade. This has dimmed the prospect of a renaissance and reignited talk of global decline.

A closer look at the incumbents in the nuclear TIS highlights the struggles faced by many firms. All private, North American firms (WE, CE, GE, AECL) have exited the TIS (see Table 3), as has German Siemens. Other firms, such as Framatome, Toshiba, and Hitachi, face an uncertain future, with few projects in the pipeline and ongoing constructions plagued with difficulties. Among Framatome's six reactors currently under construction, two—Olkiluoto-3 and Flamanville-3—have

Table 2
Indicators and data sources.

	Indicator	Operationalization	Data source
Actor base and TIS size	Key actors	Reactor technology developers	General web search, [45]
	Firm entries/ exits	Entries by newcomers; exit or scaling back of commitment by reactor technology developers	General web search, news articles; [45]
	Market size and technology diffusion	Installed reactor capacity per year; cumulative installed capacity	[38, 45]
Institutional structure and networks	Regulation and policy support	Phase-out or anti-nuclear policies (at national levels); R&D (expenditures, composition) of key countries	[48-50]
	Networks	Customer-supplier relationships	[45]
	Expectations	Expectations about the future of nuclear among industry proponents and international forecasts	IEA's *World Energy Outlook* (various years)
Technology performance and variety	Performance	Installation costs	[37, 51, 52]
		Maximum plant capacity (economies of scale)	[45]
		Cost and time overruns	[37]
	Technology diversity	Reactor types and design variants; new reactor types	[45]
Context: TIS-context relationships	Wider context	Qualitative description of key developments	Diverse sources (see text)
	Competing and complementary technologies	Qualitative description of interactions with other technologies and sectors	Diverse sources (see text); [38, 53]

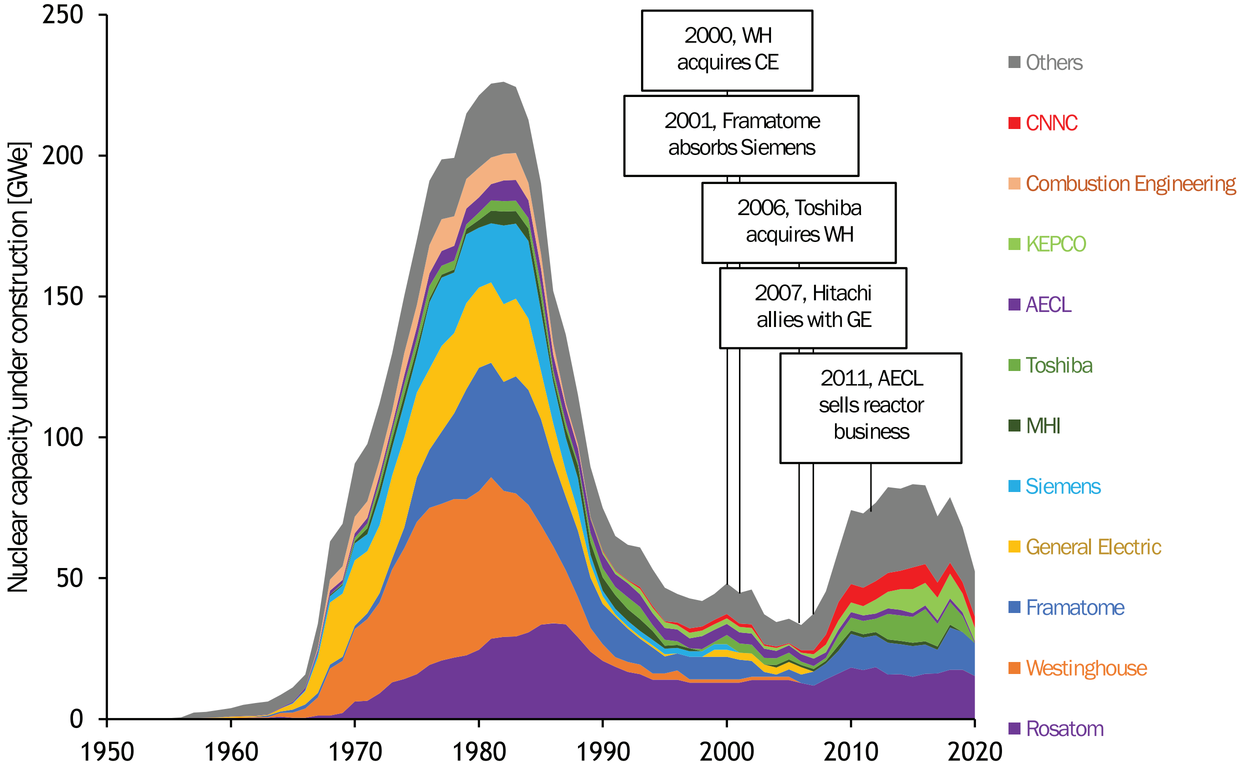

Fig. 4. Nuclear power capacity under construction by the largest reactor suppliers. *Data:* IAEA PRIS database [45]. Capacity built with two or more reactor suppliers was equally distributed between the firms described as suppliers (e.g., one 1 GW reactor with two suppliers appears as 0.5 GW per supplier). Capacity under construction after a merger or acquisition was allocated to the acquirer or the largest organization. See methodology for network analysis in appendix for further details.

Table 3
Profiles of the largest nuclear reactor suppliers. Based on IAEA PRIS database (see methodology for network analysis for details on the figures for columns 1–3. Number of reactors and capacity supplied include projects with two or more reactor suppliers listed. Planned reactors represent reactors with planned construction start date available and posterior to 2019, as reported by IAEA by 31 December 2018. "Last" reactor indicates the year when construction started on the last reactor in which the firm was engaged as a supplier.

	Reactors supplied	Capacity supplied	Reactor pipeline	Country	Ownership	Relevant developments	Status
Rosatom	136	107 GW	19 ongoing 17 planned	Russia	State-owned		Active
Westinghouse (WE)	106	99 GW	5 ongoing	United States	Private firm	2006, acquired by Toshiba 2017, bankruptcy 2018, acquired by Brookfield	Exited
Combustion Engineering (CE)	15	15 GW	1977 (last)	United States	Private firm	2000, acquired by Westinghouse	Exited
Toshiba	19	18 GW	2000 (last)	Japan	Private firm	2018, exits oversea projects	Active
Framatome	94	101 GW	9 ongoing	France	State-owned	2001–2018, reorganizations	Active
Siemens	39	42 GW	1984 (last)	Germany	Private firm	2001, nuclear business acquired by Framatome	Exited
General Electric (GE)	73	65 GW	1999 (last)	United States	Private firm	2007, alliance with Hitachi	Exited
Hitachi	12	12 GW	2 ongoing	Japan	Private firm		Active
Mitsubishi Heavy Industries	23	19 GW	2009 (last)	Japan	Private firm		Active
Atomic Energy of Canada Ltd (AECL)	38	24 GW	1998 (last)	Canada	State-owned	2011, sold reactor business	Exited
China National Nuclear Corporation (CNNC)	20	15 GW	4 ongoing	China	State-owned		Active
Korea Electric Power Corporation (KEPCO)	22	25 GW	7 ongoing	South Korea	State-owned		Active

seen their cost triple and construction times more than double [57]. Toshiba-owned Westinghouse filed for bankruptcy protection in 2017 as nuclear projects in the southern US suffered long delays and spiraling costs [58]. One year later, in 2018, Westinghouse emerged from bankruptcy. It was sold to an asset-management firm and now focuses on nuclear services rather than reactor construction [59]. Toshiba itself announced in 2018 the closure of its UK NuGeneration subsidiary, which was in charge of building a new nuclear power plant in Cumbria [60], stating that it was an "economically rational decision" to withdraw from the UK project. Soon afterwards, Hitachi announced that it would also halt its work on the UK Wylfa nuclear power plant project [61].

At the same time, Rosatom, KEPCO, and CNNC seem to be doing fine. Rosatom has the largest pipeline of ongoing (15) and planned (29)

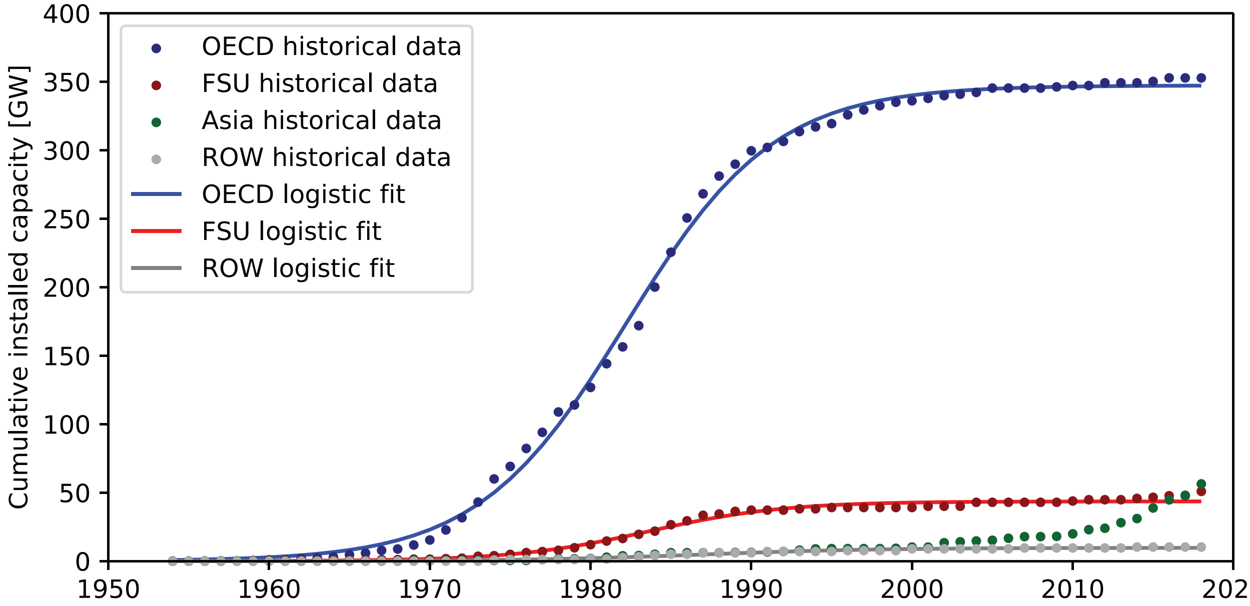

Fig. 5. Cumulative installed capacity of nuclear power by region. Logistic fits with the following estimated parameters (for OECD, FSU, RoW): saturations (347, 43, 10 GW), inflection points (years 1983, 1982, 1984), and diffusion speed (22, 20, 18 years). R^2 higher than 98.9%. Asia still exhibits exponential growth, for which we cannot reliably estimate a future level of saturation.

nuclear constructions, most of them in its Russian home market. CNNC and KEPCO have smaller portfolios, and also focus on their respective domestic markets. KEPCO, however, is building a nuclear power plant in the United Arab Emirates with four APR-1400 reactors, a design that it submitted for approval in the US [62], signaling its intent to potentially target other foreign markets. Rosatom also builds reactors abroad.

In summary, we observe three main developments in the actor base: consolidation and exit of private firms, survival and also two new entries of state-owned enterprises, and a general shift from Western to Eastern firms. It has to be noted that in recent years, new entrants and start-ups have also entered the broader field of nuclear power generation, as they take an interest in building a new type of small modular nuclear reactor (SMR). We will analyze SMRs as a development of the TIS context in Section 5.4.

5.1.2. Market size and technology diffusion

The TIS expanded rapidly in terms of generation capacity during the 1970s and 80s. Fig. 2 shows how the market grew and shrank in two distinct waves over time. Fig. 5 depicts technology diffusion in terms of cumulative generation capacity. Meanwhile, we see saturation in most regions.[5] In the OECD, it took nuclear 22 years to diffuse from 10% to 90% of the estimated saturation, although the timescale was slightly shorter in the Former Soviet Union (FSU) (20 years). In Asia, the picture is different. We currently see an “unfinished” diffusion curve, which can be interpreted as a clear sign of vitality. Also note that the overall demand for electricity has flattened in OECD and FSU countries, while it is growing in emerging economies such as China or India. China, in particular, has ambitious plans for new nuclear construction [63].

Another aspect of recent market development is that plans for new nuclear power stations, and even ongoing constructions, are being abandoned in countries with a long nuclear tradition. Here, we provide some examples for illustration. The VC Summer nuclear station in the US cost the utility and public more than US$9 billion before cancellation, capturing the attention of major news media, while sowing public distrust and spurring opposition movements [64]. The project ran into serious delays, with public reports citing new module designs, manufacturing and production challenges, lack of appropriate labor, and QA/QC issues [65]. As noted, the UK has experienced similar developments, with Hitachi withdrawing from the Wylfa project in Wales in 2019 and Toshiba pulling out of a project in Cumbria in 2018 [66]. Many of these projects have suffered from a declining TIS base, a lack of experience in new construction, or shortage of skilled work force. The French nuclear industry, for example, is confronted with less and less students who want to study nuclear engineering [67].

5.2. Institutional structure and networks

Nuclear energy is highly institutionalized, i.e., there is a dense web of institutional structures that support, guide, and constrain the nuclear TIS. These include safety standards, licensing procedures, R&D programs, phase-out policies, collective expectations, etc. Another essential structural attribute of the TIS is the network of technology suppliers (here: reactor builders) and customers (here: owners of nuclear power stations). In the following, we look at general policy support, R&D, and the supplier-customer network.

5.2.1. Regulatory and political support

One important development is that, in many countries, safety regulations have been tightened over time, and licensing procedures have become more complex as participation in nuclear planning has been opened up to a broad range of stakeholders. These developments have increased the duration and costs of planning and licensing [68].

A related issue is public opposition to nuclear. This hostility encompasses nuclear weapons as well as the risks originating from civil nuclear technology in all parts of the nuclear value chain, including mining, fuel processing, plant operation, waste transport, storage, and disposal [69]. Major nuclear accidents in the US, the former Soviet Union, and Japan sharply galvanized public opposition to nuclear around the world, and several countries suspended the construction of new reactors or even implemented phase-out policies to shut down their existing ones. Also, growing anti-nuclear movements have mobilized support for passing local and municipal-level zoning regulations that

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[5] Note that the logistic function necessarily imposes a leveling off, which only applies to some regions. The global curve (Figure 2, yellow line) shows strong growth in the 1970s and 80s, and a continued, lower growth thereafter (without saturation).

Table 4

Countries' policies pro and anti nuclear power. *Source:* IAEA, 2018. "Countries in" refers to the cumulative number of countries that built at least one nuclear reactor in the respective year or before. "Countries out" denotes the cumulative number of countries that, after building a reactor, have decided to phase-out nuclear energy—or impose significant constraints, such as a moratorium on the construction of new reactors.

Year	Number of countries in (cumulative)	Number of countries out (cumulative)	Countries opting out
1970	21	0	—
1980	31	1	Austria
1990	35	4	Spain (moratorium, ban in 2019), Philippines, Italy
2000	35	6	Belgium, Germany
2010	35	6	—
2018	39	10	Switzerland, Lithuania, Taiwan, South Korea

prohibit new power plants from being sited near urban areas. At the same time, it is worth noting that different societies and governments have reacted in different ways—e.g., to the Fukushima accident [70].

Table 4 shows the cumulative number of countries that have decided to phase out nuclear completely, and those that have opted to begin using it for electricity generation, decade by decade. More than 25% of the countries that had begun to use nuclear energy have since decided to abandon it. While this proportion may seem small, we have to consider that an outright technology ban is a rare kind of policy intervention that is often used to settle highly controversial issues following an intense political debate. Also, there are more countries that have banned nuclear without ever using it (e.g., Ireland, New-Zealand, Denmark) or those that had plans but abandoned them (e.g., Greece, Cuba).

At the same time, some countries have also decided to venture into nuclear in recent years. These include UAE, Belarus, Bangladesh, and Turkey. This underlines that there is significant variety when it comes to the political evaluation of nuclear.

A third issue is the development of public R&D funding. Advanced economies that support nuclear have typically subsidized public research to promote innovation in nuclear technology. This has been especially true in the US. However, US public research expenditure on nuclear technologies has been declining as a proportion of total energy research spending since the 1990s [49, 50]. This also mirrors global trends in nuclear spending, which has declined in relation to research spending on renewables and fossil-fuel electricity sources [71, 72].

R&D spending has also been a critical feature in maintaining a skilled workforce with state-of-the-art nuclear training and technology. The decline in spending could be associated with the loss of industry jobs, technological breakthroughs, and innovative business models that would support a healthy industry. Private research and investment have also lagged, as many venture firms require initial start-up investment from government sources.

5.2.2. *Network of customer-supplier relations*

In order to explore TIS structure, we analyze the development of the global network of nuclear reactor suppliers and the owners of nuclear power stations between 1950 and 2030. We focus on the relationships during reactor construction. In the network, nodes represent either a nuclear reactor supplier or an owner (customer), and links represent customer-supplier relationships during reactor construction. Links run in the direction from reactor suppliers to customers, and disappear once construction is completed (see supplementary information for details).

During the 1950s, TIS development began with many small reactors, mostly built by private British and American firms. The customers were state-owned utilities such as the Central Electricity Generating Board (CEGB) in the UK or Electricité de France (EDF) in France. In the 1960s, constructions tripled, suppliers doubled, and reactors grew larger. Two American firms, Westinghouse (WH) and General Electric (GE), supplied more than half the nuclear capacity created during this period. Customers grew more numerous and diverse, with a larger fraction of private electric utilities in the US, while elsewhere state-owned utilities remained by far the largest customers. The 1970s saw the highest number of reactor constructions. The number of suppliers, however, decreased by one-third, and a few large players dominated the network (star like structures around large suppliers). The TIS also continued to spread geographically, e.g., with new customers in Japan. Reactor owners continued to diversify—for example, with privately owned firms such as TEPCO in Japan.

In the 1990s, the number of constructions dropped sharply, and the network fragmented into isolated or sparsely connected elements (see Fig. 6). The number of reactor owners in the network reached an all-time low. The central network position of the American giants WH and GE waned after constructions in the US halted. This left the Japanese, Russian, French, and Korean hubs only very loosely connected, if at all. In the 2000s and 2010s, the network has been giving off ambiguous signals. New connections have appeared (since mid-2000) as the number and capacity of reactors under construction grew again. More reactor suppliers have got involved, and activity in Asia has re-connected the French, Japanese, and American hubs. Similar to the shift in reactor suppliers (see Fig. 4), the industry has pivoted towards state-owned customers in Asia and Russia, led by CGN and CNNC in China. Other signals, however, suggest continued stagnation. The network still has only very few nodes, with few connections. Reactor suppliers became increasingly dependent on a handful of large customers, such as China's CGN and CNNC, who ordered nearly half of new constructions in the 2000s and 2010s.

Looking beyond 2020, just one firm, Rosatom, has new reactors planned with a fixed construction start date. All are located in its home country, Russia, although it has others abroad—in Turkey, for instance—but with no start date for construction [45].

5.2.3. *Expectations*

Expectations concern shared beliefs about the future of the TIS. Here, we look at forecasts. We compared the projections for nuclear power generation (in terms of both absolute production and relative share) published by the International Atomic Energy Agency (IAEA) in its annual Energy, Electricity and Nuclear Power Estimates and by the International Energy Agency in its flagship report *World Energy Outlook* (WEO). These forecasts are widely watched by industry actors and policy makers, and describe themselves as the "gold standard of long-term energy analysis" [73]. We only show the highest, i.e., most positive estimates.

Fig. 7 shows absolute (columns) and relative (lines) values for the target years 2020 (blue, dotted) and 2030 (red, solid). Our findings show a clear decline in the prospects for nuclear power following the Fukushima accident in 2011. The forecasts of both organizations are consisten in this. The forecasts also became more cautious in recent years. In 2018 reort, the IAEA reported increased uncertainty around the retirement of existing reactors: "Compared with the 2017 projections to 2030, the 2018 projections were reduced by 45 gigawatts (nameplate capacity) (GW(e)) […]. These reductions reflect responses to the Fukushima Daiichi accident and other factors noted above. There are increasing uncertainties in these projections owing to the considerable number of reactors scheduled to be retired in some regions around 2030 and beyond. Significant new nuclear capacity would be necessary to offset any retirements resulting from factors such as ageing fleets and economic difficulties." [74, p. 3].

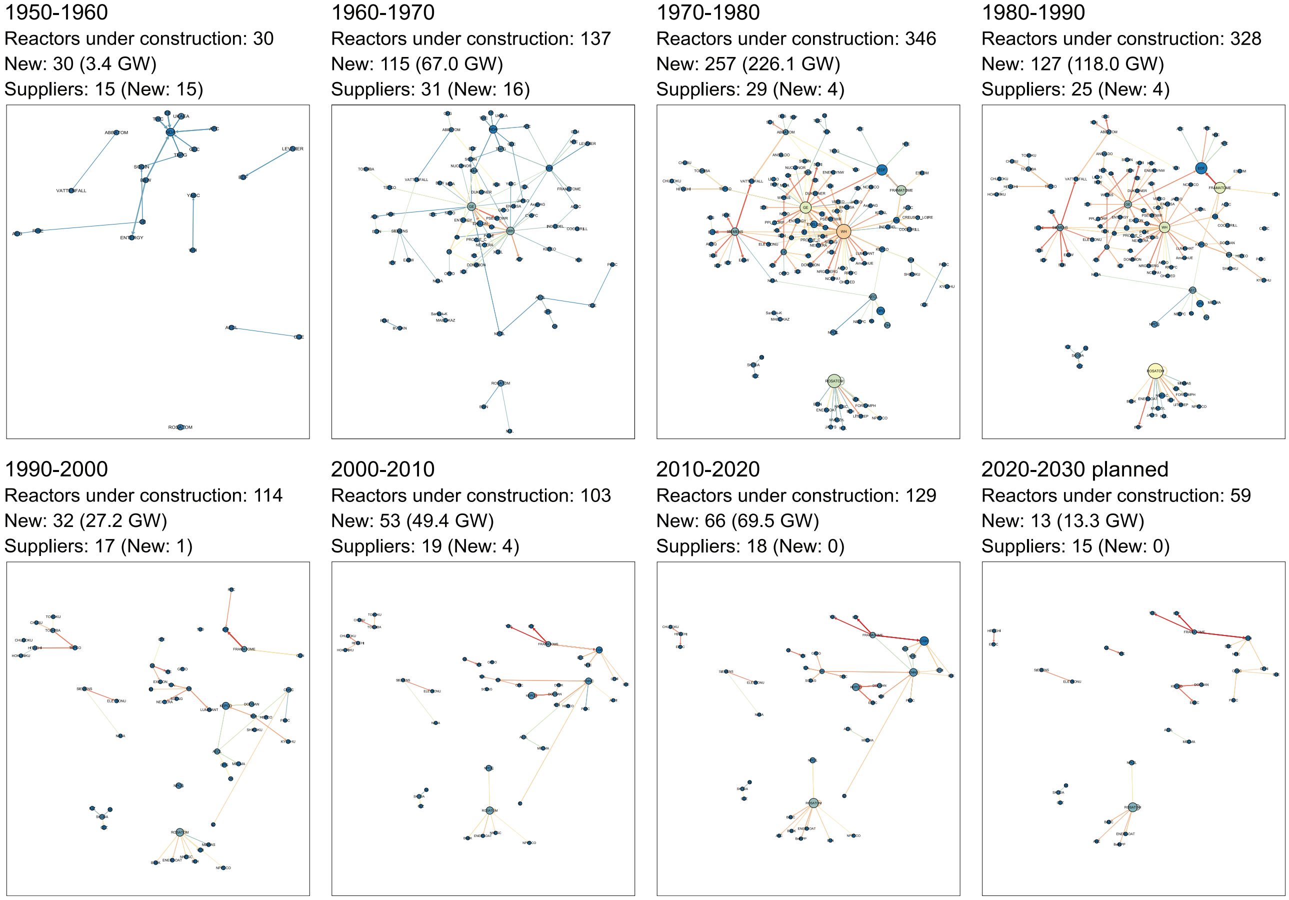

Fig. 6. Evolution of the global network of reactor suppliers and owners between 1950 and 2030. *Data:* IAEA PRIS. Nodes represent nuclear reactor suppliers and owners. A few nodes (e.g., Rosatom) supplied themselves with nuclear reactors, which is represented with self-loops. Ties (links) represent customer-supplier relationships. Node size of customers is constant. Node size of suppliers is proportional to the nuclear capacity they deliver. Link thickness and color represent the capacity under construction in the relationship (i.e., the more capacity, the thicker and darker red the tie).

The continuous downscaling of expectations clearly paints a dismal picture for the prospects of the nuclear TIS, especially as these are the most positive scenarios, coming from organizations that have always been very much in favor of nculear.

5.3. Technology

5.3.1. Costs and plant size

For many energy technologies, costs typically decrease over time thanks to learning effects that co-occur with technology diffusion. Technologies such as nuclear seek to reduce costs by upscaling, in order to reap economies of scale [75]. While the first reactors were below 100 MW in size, unit capacities reached 800 MW in the 1970s and 1,400 MW in the 1980s.

However, the expected cost reductions did not materialize. Indeed, costs even increased, exhibiting what some scholars have called “negative” learning [51, 76, 77]. For example, costs doubled in France, and rose by a factor of as much as five in the US between 1970 and 1990.

Several factors contributed to this particular development. First, the lumpiness and complexity of nuclear technology limit the potential for cost reductions [51]. Second, technology scale-up increased system complexity, raising the requirements for, e.g., safety standards or fuel cycle management [78]. Third, resistance against nuclear intensified, leading to longer planning and licensing times [37]. Finally, another factor is knowledge obsolescence and the erosion of institutional capability [79], given the dearth of new-reactor constructions in recent years along with a reduction in network density (see Section 5.2.2). Some scholars dubbed this phenomenon “learning by forgetting” [51, 80]. It is this last development, in particular, that points to an industry in decline.

5.3.2. Construction times

Construction times for large-scale, complex technologies are typically long. Nevertheless, they can be expected to grow shorter over time, due to standardization and an accumulation of experience. In the case of nuclear, average construction times were around five years or less at the outset, climbing to an average of around 10 years in the 1980s and after [37]. Average construction time has become not just longer, but also less predictable, especially in recent years (Fig. 8). In its latest report, the IEA writes that “Construction problems, project delays and cost overruns are scaring off investors” [38, p. 22].

Time overruns typically lead to cost overruns (by imposing additional requirements in terms of human resources, capital costs, etc.). For nuclear power, the relation is clear and strong. We find that time overruns for reactor construction explain more than 60% of the cost overruns of projects (Fig. 9). There is no clear trend in the development of time and costs overruns over time. Overruns have persisted, if not

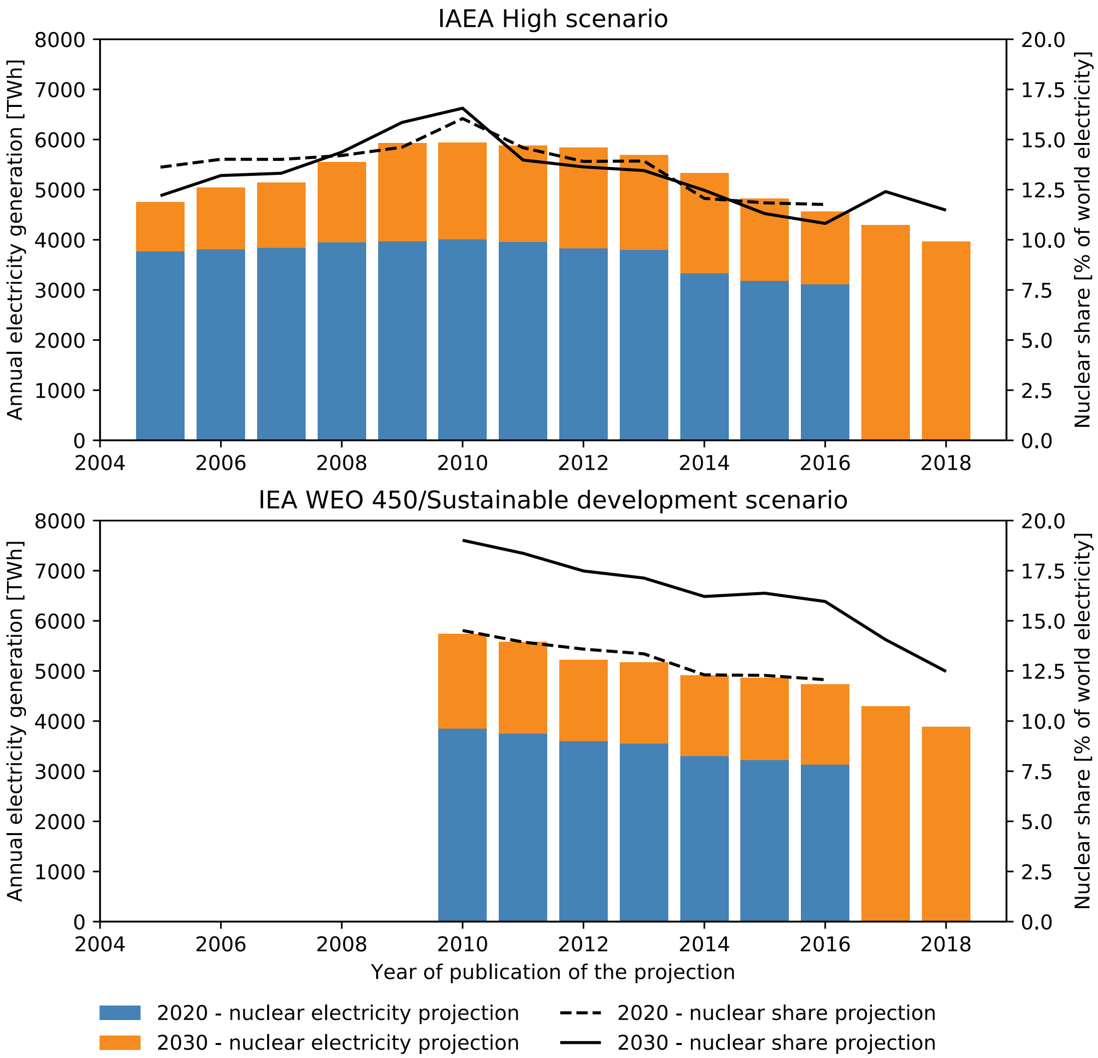

Fig. 7. Change of forecasts for nuclear energy.

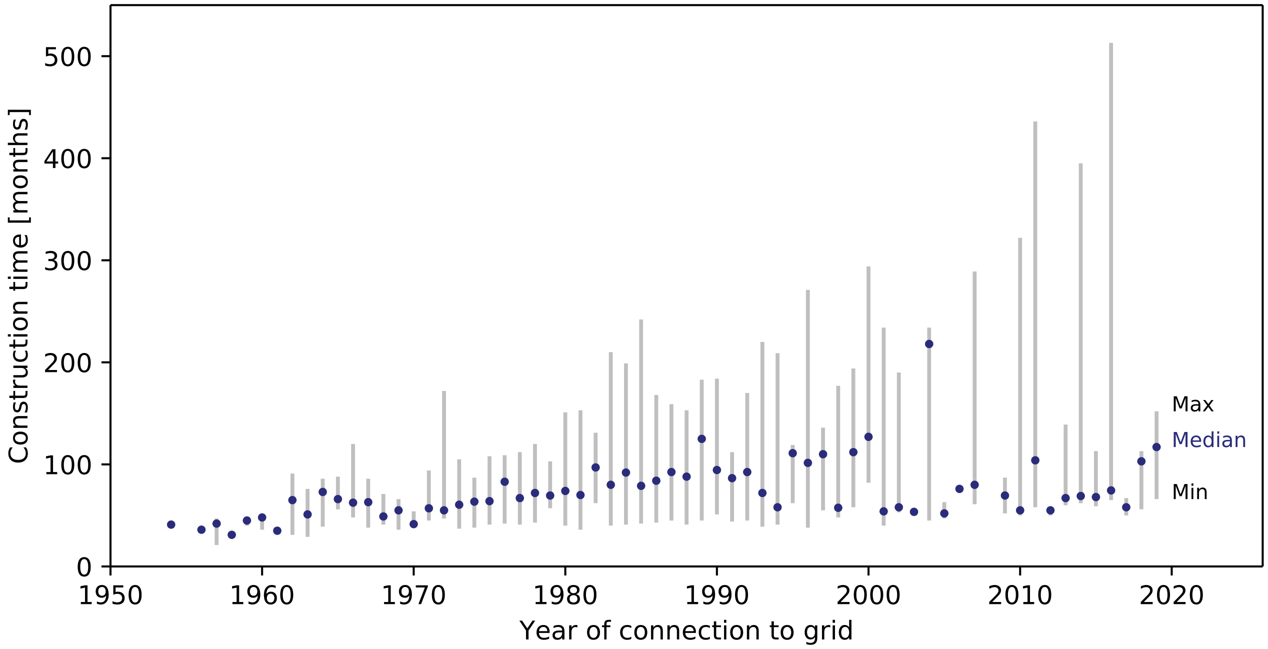

Fig. 8. Uncertainty in the construction time of nuclear reactors. *Source:* PRIS database.

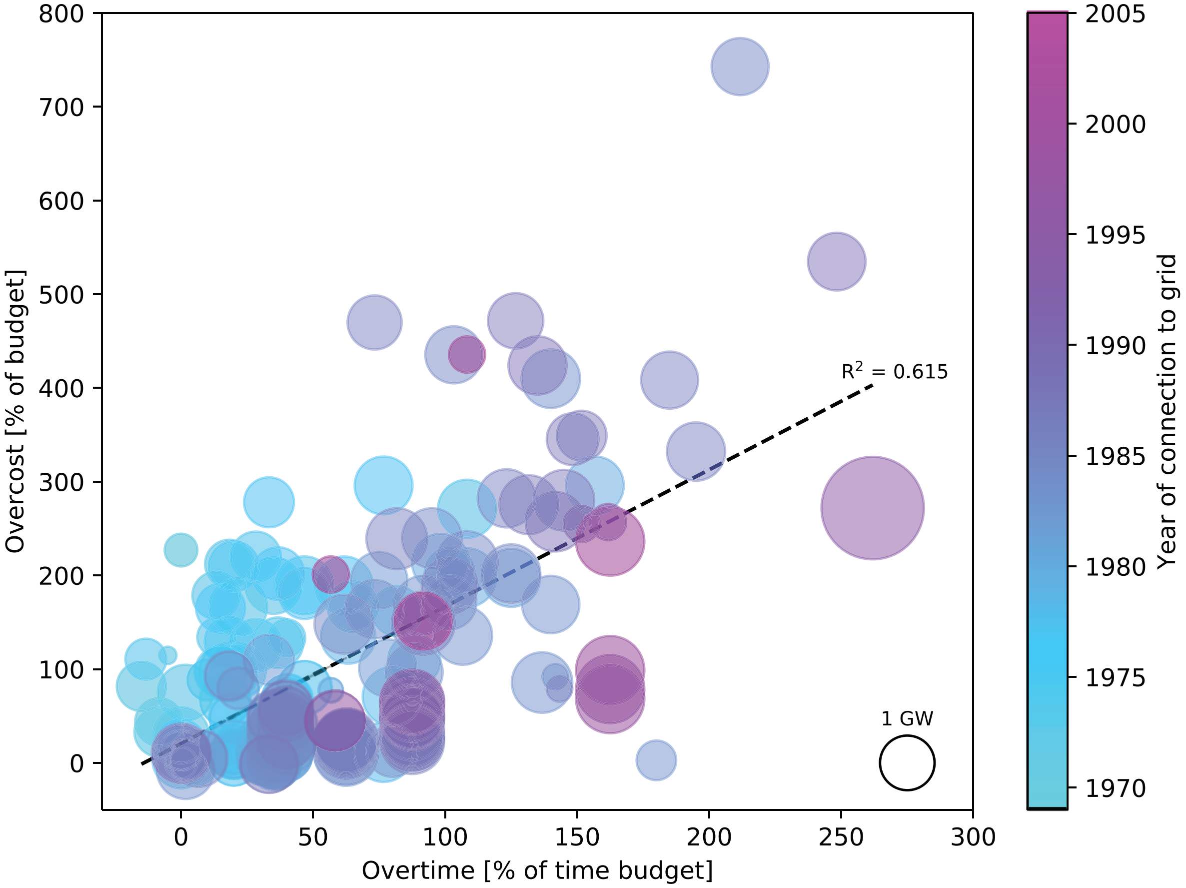

Fig. 9. Cost and time overruns. *Source:* Sovacool et al., 2014.

actually worsened, in recent years; many can be attributed to issues with planning new reactors (e.g., financial stress, contractor problems, social resistance). It may also be that reactor suppliers make unrealistic offerings in order to secure a contract in the first place, hoping to renegotiate conditions later.

5.3.3. Variation

Decreasing variety (which can further enhance economies of scale) is a well-known indication of technology maturity. Fig. 10 shows the concentration index (Herfindahl-Hirschman, HH) over time for reactor types and models[6] connected to the grid in the respetive year. We find that diversity of reactor types increases (concentration decreases) up to the end of the formative phase around 1970. Since then, the industry has concentrated on fewer and fewer types of reactors. In recent years, Pressurized Water Reactors have become the dominant design for new reactors. PWRs are reportedly safer than other types, but also have higher material requirements [51].

While concentration on reactor types is high, there is still variation in terms of their variants/models. We interpret this as an indication that incremental innovation (i.e., at the level of models) is still ongoing, while architectural innovation (i.e., at the level of types) has reduced. Such a development can be expected for a mature industry. The particularity, however, is that the convergence around a dominant design and subsequent incremental innovations have not resulted in cost reductions.

In summary, technology performance is riddled with challenges. These include high costs, substantial cost and time overruns, and little diversity.

5.4. TIS context relations

Here, we study the TIS context, including wider contextual developments, alternative generation technologies in the electricity sector, and the military sector (Fig. 11).

5.4.1. Wider context

The nuclear TIS has been affected by a variety of developments in the broader context (black arrows in Fig. 11), the most important of which are market liberalization, nuclear accidents, climate change, rapidly growing electricity demand in emerging economies, and geopolitics. Liberalization and accidents have had negative effects; the effects of climate change and demand growth are mixed; and geopolitics has positively affected the TIS.

First, electricity supplies were liberalized and privatized in many countries during the 1990s and 2000s. Market liberalization eroded the monopolies and political structures on which nuclear power depended [81, 82]. “The biggest barrier to new nuclear construction is mobilising investment. ... [D]oubts [about the size of investments] are especially strong in countries that have introduced competitive wholesale markets” [38, p. 4].

Second, the history of nuclear energy has included several major accidents[7]. Over and above their cost in human life, these have had severe impacts on ecosystems and local communities, and required extremely costly and dangerous cleanup missions, some of which are still ongoing. The three best-known nuclear accidents are Three Mile Island (US, 1979), Chernobyl (Ukraine, 1986), and Fukushima (Japan,

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[6] As with civil airplanes, where various product families are clearly distinguished by the model code, the reactor model (initials before the number) identifies both the technology generation and the variants within it.

[7] We decided to situate nuclear accidents in the context because they came as uncontrollable, external shocks to most TIS actors. Of course, nuclear accidents are at the same time intrinsically tied to the focal technology.

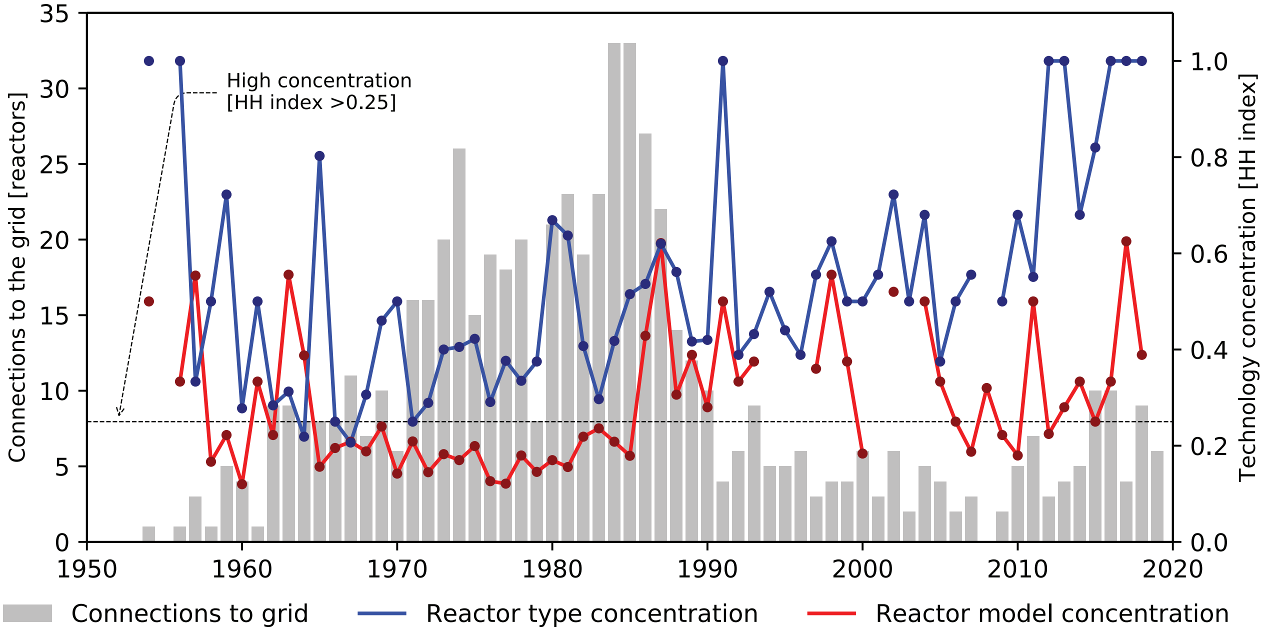

Fig. 10. Concentration of reactor types and design variants (proxy for incremental innovation). *Source:* PRIS database. How to read the graph: In 2018, for instance, ten new reactors were connected to the grid (grey bars, left axis). These were all of the same type (Pressurized Water Reactors, PWR), which translates into HH =1 (blue line, right axis) but featured three different models (APR, EPR, VVER), which translates into HH = 0.4 (red line, right axis). The year before, only 4 were connected, all of the same type (HH = 1) with two different models (HH = 0.6).

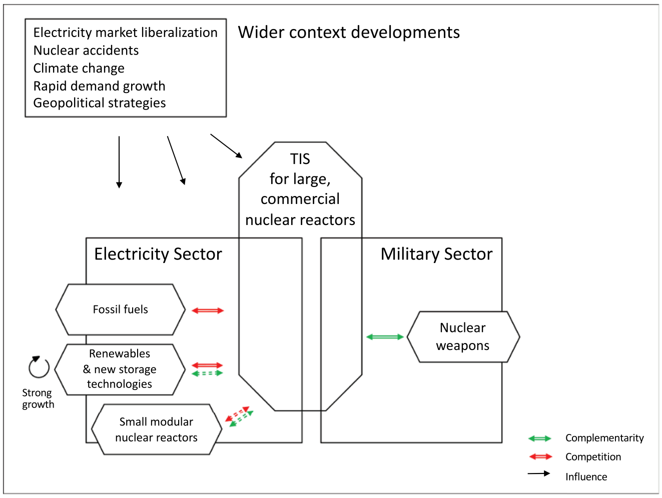

Fig. 11. Focal TIS and interactions with contextual elements.

2011). Each one severely undermined the legitimacy of nuclear technology [83] and fueled public opposition to it. In response to these accidents, several countries took policy decisions to phase out nuclear altogether (cf. Section 5.2.1).

Third, climate change has rekindled hope for nuclear [38]. Research has shown that nuclear proponents use the climate challenge in order (re-)frame nuclear as a sustainable, emission-free technology, in an attempt to re-establish its legitimacy [84]. “We contend that, as of today and for decades to come, the main value of nuclear energy lies in its potential to contribute to decarbonizing the power sector” [39, p. xvii]. Scholars also argue that nuclear is not only low-carbon, but can also supply bulk energy in a non-intermittent fashion [81]. Nonetheless, climate change has a mixed effect, as it also stimulates the development of renewable energies, which compete with nuclear (see below).

Fourth, rapidly growing economies such as China, India, and South Korea have had a strong impact on power-generation technologies, including nuclear. China and South Korea became key markets for new nuclear around 2010 and subsequently, due to increasing demand for electricity and existing nuclear infrastructure. However, rapid demand growth also fueled the expansion of coal, wind, and solar in these markets [85].

Finally, geopolitical and industrial policy considerations affect nuclear in a positive way. States such as the US and the FSU—and, more recently, Russia, China, and South Korea—have been actively pushing for the construction of nuclear reactors beyond their borders, with important geopolitical considerations in mind [86, 87]. For example, Rosatom is currently building one nuclear reactor in Turkey, and has recently been granted the license for a second [88]. Such investments create economic and political ties between the countries and firms involved. A recent study also points to the growing control of Russia over some parts of the nuclear value chain [89].

5.4.2. *Competing and complementary technologies*

The main competitors[8] to nuclear (the red arrows in Fig. 11) are fossil fuels, as well as renewables such as wind and solar PV with battery storage. One of the key challenges in the competition between nuclear and other power-generation technologies is the relatively high cost of nuclear [39]. Environmental and sociopolitical issues (e.g., loss of legitimacy and political support) also play a major role.

Renewables are a particularly important competitor, because they are still growing rapidly with high rates of technological learning [71, 90]. In many large economies (e.g., China, Germany, India, UK), power generation from non-hydro renewables has already surpassed generation from nuclear [72]. Further sharp falls in the cost of renewable technologies are likely to undermine the economic competitiveness of nuclear still further [53]. Recently, the competition between nuclear and natural gas has been intensified by innovation in fracking. Fracking has lowered the price for natural gas significantly, making new investments into gas-fired power plants very attractive in comparison to new nuclear.

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[8] Applies to current electricity systems. In a low-carbon future, lines of competition might be very different, e.g. between different kinds of flexible / dispatchable generation.

Further competition to large-scale nuclear power may also arise from small modular reactors (SMRs). Even though their future prospects are uncertain (hence the dotted arrow), SMRs have been billed as a potential alternative to large centralized reactor designs with promises around improved safety, flexible expansion of generation, and, most importantly, reduced costs and deployment times due to modular construction [39, 91]. SMRs are usually defined as nuclear reactors with nameplate capacity under 300 MW. Many reactor types are in use, including pressure-water reactors and molten salt reactors. In Russia, Rosatom has just built two floating 35 MW reactors on a vessel to supply a remote city in the Arctic [92].

Expert assessments vary widely on the financial and technological viability of SMRs as an option to replace large-scale nuclear power [93]. Cooper [90] concludes that the lack of R&D investment for sustained support of SMRs indicates a significant future challenge, while other authors question whether policy environments will be favorable enough [94]. Moreover, SMRs would also have to confront the issues that remain with all nuclear technologies, including radioactive waste, water consumption, and thermal pollution [95, 96].

Complementarities for nuclear power (green arrows) arise in countries that rely on nuclear weapons, because nuclear reactors are needed to produce raw materials, e.g., plutonium, for use in such weapons. In some countries, civil nuclear is also used as a cover for nuclear weapons. Furthermore, civil and military nuclear technology also complement each other in terms of research and educational programs, skilled workforces, or industrial capabilities [14, p. 174]. In fact, the two realms have long had a close relationship, and most commercial reactor designs are derived from military-purpose reactors (ibid: 175).

While different generation technologies compete at the technology level, they may complement each other at the level of the electricity sector [23]. In low-carbon power systems, nuclear may complement generation from solar or wind (dashed green arrow; [97]. In a similar vein, SMR technology might complement nuclear in the long run, due to potential technology spillovers.

5.5. Summary

We found many indications that, at the global level, the nuclear TIS is in a phase of severe crisis and decline. In terms of actor base and market size, the TIS has been declining since the 1990s, and many of the former key reactor suppliers have exited the industry or fundamentally reorganized their business. Firms are even withdrawing from ongoing construction projects because of escalating costs. In terms of regulatory support and networks, the legitimacy of nuclear has deteriorated; several countries have formulated phase-out policies; and supplier-owner networks have thinned out dramatically. In terms of performance, costs are the main problem, but increasing uncertainty over construction times is an issue too. With regard to contextual developments, the biggest challenge is fierce competition from incumbent (coal and gas) and new (wind, solar, batteries) technologies in liberalized electricity markets.

At the same time, we also found some positive developments for nuclear. There was a smaller wave of new constructions around 2010, led by China (cf. Fig. 4). During this period of revival, new business relationships and small supplier-owner networks also emerged (cf. Fig. 6). Also, the increasing attention to climate change and growing interest in low-carbon technologies may work in favor of nuclear. Moreover, geopolitical strategies, as well as traditionally strong ties with the military, serve to protect the development of new nuclear technologies in some countries.

In summary, we conclude that the overall picture is negative. Many indicators show a deterioration of TIS performance. In particular, the fact that the costs of nuclear and those of competing low-carbon technologies continue to drift apart severely undermines the future prospects for nuclear.

6. Discussion

Our study is not the first to find that nuclear technology is in decline. As early as 1977, the IEA stated: “It is nuclear power, however, where the greatest short-fall from earlier expectations has occurred” [98, p. 12]. Scholars who studied nuclear in the US back in the 1980s saw the “collapse of an industry” [56] and argued that “renewed growth of nuclear power in the United States is unlikely” [99, p. 295]—an assessment that, from today's perspective, turned out to be prescient.

Our study is also in line with recent reports from IEA and MIT, which identify similar problems and arrive at similar assessments to ours regarding the overall prospects of nuclear. “Despite this promise [of nuclear as a dispatchable, low-carbon technology], the prospects for the expansion of nuclear energy remain decidedly dim in many parts of the world. The fundamental problem is cost” [39, p. xi]. “The hurdles to investment in new nuclear projects in advanced economies are daunting. ... The main obstacles relate to the sheer scale of investment and long lead times; the risk of construction problems, delays and cost overruns ...” [38, p. 4]. These studies go on to highlight the importance of nuclear for the ongoing low-carbon energy transition. As a consequence, they call for public policy support to stimulate investments and recommend strategies to bring down costs [38, 39].

6.1. Nuclear decline and the ongoing energy transition

The transition to low-carbon energy affects the future of nuclear, and vice versa. We have argued above that the transition can benefit nuclear, as fossil fuels are under increasing pressure. But the transition is also a threat, because renewables continue to improve [53]. In the US and Europe, the levelized costs of electricity for new nuclear power plants are higher than those of both onshore wind and solar PV. This even holds for solar PV plus storage, and when accounting for the variability of renewables [72, p. 28].

The decline of nuclear is also a challenge for the low-carbon energy transition. First, renewables will have to replace not only fossil fuels, but also the aging fleet of nuclear power plants, many of which will go offline in the near future (up to a quarter of the 315 GW reactors installed in “advanced economies” will be shut down by 2025 [38, p. 15]. Currently, it seems that a key policy strategy is to extend the lifetime of existing reactors in order to produce as much low-carbon electricity as possible before their eventual closure [38]. Second, views differ on whether nuclear will be compatible with deeply decarbonized electricity systems. Some argue that nuclear can respond to variations in demand and supply, and therefore offer lower overall system costs [97], while others question its flexibility [100]. Third, there is a broader issue of *technology diversity* at stake here [24]. As industry networks weaken globally, it will be much harder to come back to nuclear technology in the future. Complex technologies such as nuclear require “sophisticated” technological innovation systems that provide highly qualified personnel, specialized industry capabilities, and broad sociopolitical and institutional support. Once lost, these may be onerous, or even impossible, to rebuild.

The issue of diversity also has broader policy implications: What is a “good” level of diversity, and what is it worth? And how should we deal with the trade-off between accelerating transitions (given the urgency of climate change) and a reduction of diversity (including the risk of renewed lock-in)?

Of course, nuclear decline may also represent an opportunity for the energy transition, as it strengthens the trend away from centralized systems and towards decentralized ones [101]. This opens up new space for alternative configurations, based on distributed renewables, local storage, smart grids, demand-side management, and energy efficiency [21].

6.2. Indicators for studying decline

As we also want to improve the analysis of decline processes more generally, we briefly discuss our indicators. One challenge when using multiple indicators is that they might not all point in the same direction. For some of the indicators, Fig. 12 depicts a stylized comparison of the heyday of nuclear in the 1970s and its current phase of development (see also Table 5). We do not present this to reiterate the implications for the future of nuclear, but rather to address some conceptual issues. First, what is an appropriate benchmark to assess whether a TIS is in decline? If we assume an ideal-type lifecycle (formation, growth, maturity, decline), the peak of diffusion in the mature phase would be a suitable benchmark. In the case of nuclear, however, we see market dynamics with an early decline in the 1980s and a smaller revival after 2010 (Fig. 4). This is why we shifted the benchmark to the beginning of the 70s—the end of the formative phase. Alternatively, we could have also compared with the second, smaller peak—but as this phase is still ongoing, the assessment would be less reliable.

Another issue is which indicators to include, and which, if any, to prioritize. We believe that it is important to focus not only on economic indicators, as industry lifecycle studies do [55, 102], but also on institutional, technological, and contextual developments, as suggested for TIS studies [17, 26]. Also, we tried to treat all indicators equally, knowing that other studies focus on specific indicators such as technology performance and costs [97, 103, 104]. With a broad approach such as ours, the picture is more comprehensive, but it also demands a much greater effort in terms of data collection and compilation.

A third and more foundational issue is whether to use indicators in the first place, or put more effort into qualitatively tracking specific *processes of decline*, and how they interact.[9] Our findings seem to indicate that factors such as the loss of legitimacy, additional safety requirements, longer licensing procedures and construction times, and rising construction costs reinforce each other, possibly creating negative feedback loops. Such *vicious cycles in decline* are certainly an issue that requires further research.

This also links nicely with the procedural (functions) perspective in TIS studies [16]. Our findings suggest that the exit of central actors (undermining entrepreneurial experimentation); increasing regulatory pressure (direction of search); the loss of legitimacy (legitimation); market decline (in contrast to market formation); and the weakening of industry networks (in contrast to positive externalities) are all part of the ongoing decline in nuclear. However, a systematic analysis would be required to conceptualize and analyze decline from a "functions" perspective.

6.3. Limitations

Our study has several limitations. As we concentrated on the main

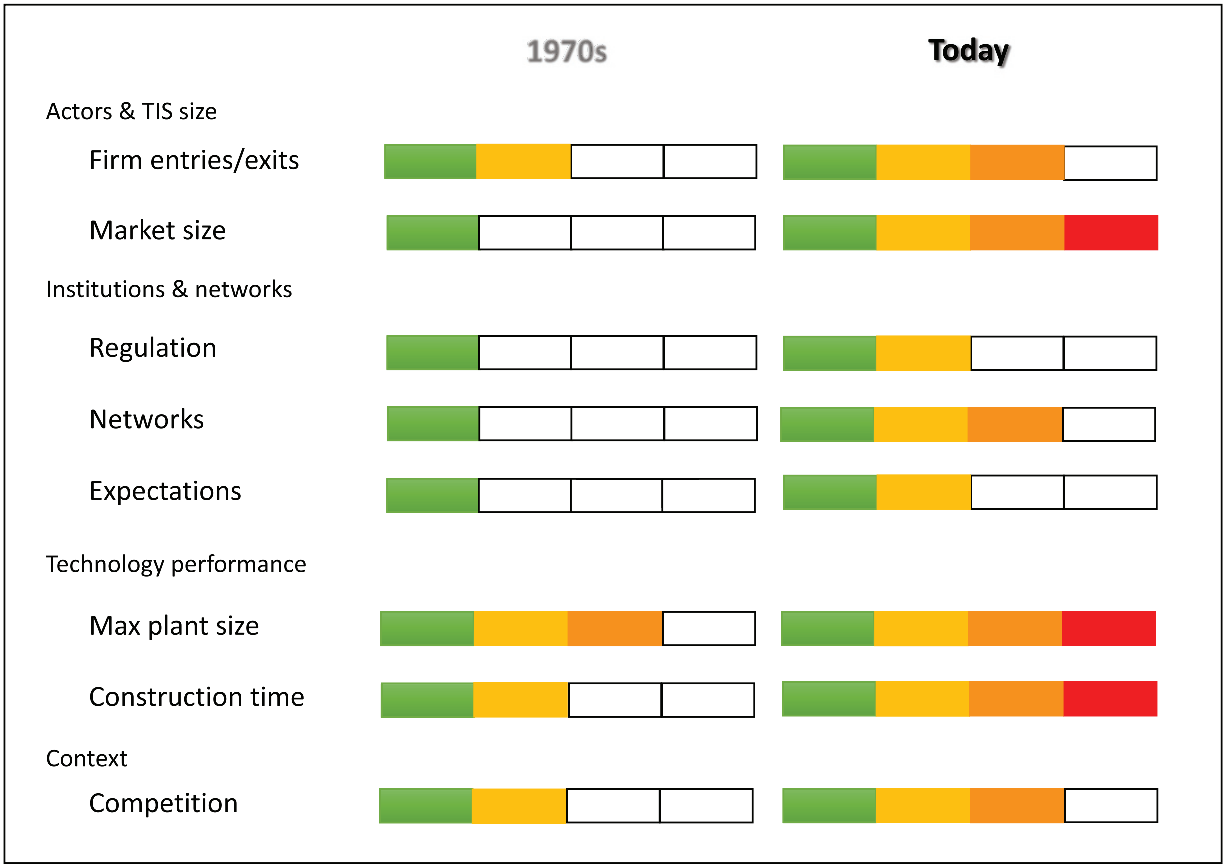

Fig. 12. Current status and comparison with the growth phase in the 1970s. The colored bars show how the TIS is doing. One bar (green) means little or no problems, while four bars (red) signify major problems and point to potential decline. See Table 5 in appendix for details, each bar represents a 25% quartile.

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[9] In fact, this was one of the reasons TIS scholars developed the functions approach [17]. We refer to some of the TIS functions in Table 5 (appendix).

global developments, we could not account for the great variation at national levels (see Appendix, Fig. 13). For example, there seem to be key differences between countries with liberalized electricity markets and/or democratic political systems and those without. A promising follow-up study would be to analyze nuclear from a global innovation systems perspective [105] to explore the interaction of local and global developments, as well as through the lens of mission-oriented innovation policies [106]. The prospects for nuclear are much better in those countries where it does not have to compete with other technologies, but is driven by strong state interests and/or state-owned companies. Such interests can be manifold, ranging from energy independence to geopolitical and political economy motives. Even though we could not explore these issues any further, it is important to note that they matter, and are set to play a key role in future developments [89].

Moreover, nuclear is a very particular technology. First, it comprises two different markets—construction and operation—both of which have very different logics and very long time horizons. While we have primarily concentrated on reactor construction, operation plays into decline as well. Second, decline in nuclear is clearly not a rapid process characterized by powerful vicious cycles—as in consumer electronics, for example—but it is instead dragging on over multiple decades. Third, nuclear is a technology with a negative learning curve, which is very rare. Fourth, and finally, nuclear is highly political. One aspect of this is the fierce controversy and anti-nuclear protest that we see in some places. Another aspect is the geopolitical relevance of nuclear (see above). These issues are intertwined, and combine to make nuclear a special case. Therefore, we must tread carefully and reflect deeply when we come to generalize and compare nuclear with other industries in decline, such as coal-fired electricity generation [8].

7. Conclusion

This paper addresses the question of whether nuclear is in decline at a global scale. Based on a variety of indicators, we suggest that the answer is yes. Also, we have little reason to expect that a similar assessment a few years from now would arrive at a different conclusion. Overall, it seems that, globally, nuclear could become the first victim of the ongoing energy transition. However, this transition did not originally trigger the decline of nuclear; it began over two decades ago, as a result of growing opposition, more complex licensing, growing safety concerns, and escalating costs. Soon afterwards, the situation was aggravated by market liberalization. Finally, the recent success of renewable energies is making it even harder for nuclear to survive.

Does this mean that the nuclear TIS is on its deathbed? Absolutely not. Even if no or very few new nuclear power plants were to be built in the future, it is very likely that existing ones will continue to operate until the end of their projected lifetime. So, for many years into the future, there will be a demand for organizational capabilities and skilled workforces to operate, maintain, and dismantle nuclear power plants. This creates a “niche in technology decline” that could even be a seedbed for future innovation in nuclear technology.

Moreover, there are strong “state niches” for nuclear in countries such as Russia and China (and, to an extent, France), where the construction and operation of nuclear is organized by state-owned firms and/or receives substantial public support. These protected activities may be driven by political and economic considerations, to insure political influence in specific regions, and/or by the ambition to export nuclear technology.

Nuclear decline has major implications for the ongoing low-carbon energy transition. First, it undermines recent hopes that new nuclear will become a key strategy to reduce carbon emissions, or a backbone for deeply decarbonized power systems [39]. What remains is the option to further extend the lifetimes of existing reactors, and to squeeze existing assets for as long as possible [38]. Second, recent and future investments in new nuclear might suffer from the diseconomies of a declining industry, in which industrial competences become increasingly scarce and concentrated. Third, the decline of nuclear opens up new opportunities to gather experiences with electricity systems that are not dominated by major shares of baseload power. Such experiences will be crucial for deeply decarbonized electricity systems in a future without nuclear.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.erss.2020.101512.

Appendix

See Table 5 and Fig. 13.

Table 5
Indicators to track the performance of the nuclear TIS.

Type	Indicator & source	Metric [unit]	1970s (unless otherwise stated)	2010s (up to 2019)	Score*	Links to innovation system functions	Rationale
Actor base & TIS size	Firm entries/exits Fig. 6 (average of both leads to orange)	Δ reactor suppliers [#]	29	18	38% (yellow)	Market formation, resource mobilization, direction of search	Technology manufacturers exit as a result of increasing competition, high entry barriers [107]
		Δ new entrants [#]	4	0	100% (red)		
	Market size Fig. 5	% of estimated saturation [GW]	560** - 347	460(Global)-347 (OECD)	82% -100% (red)	Market formation	Increasing saturation marks beginning of decline [3]
Institutional structure & networks	Regulation banning nuclear Table 4	% of countries with bans or phase-out policies [#]	39 (2018)	10 (2018)	26% (yellow)	Legitimation, direction of search	Loss of technology legitimacy [32]
	Network structure Fig. 6 (average leads to orange)	Δ actors in largest component [#]	101	17	83% (orange)	(positive) external economies; knowledge development and diffusion	Importance of well-functioning networks [16]
		Δ connected components [#]	8	5	38% (yellow)		
		Δ communities with more than 3 actors***	9	3	67% (orange)		
	Expectations Fig. 7	Δ IAEA estimate for generation in 2030 [TWh]	5,930 (2010)	3,969 (2018)	33% (yellow)	Direction of search, legitimation	Downscaling of expectations: signaling loss of confidence [108]
Technology performance & variation	Maximum plant size [46]	% of maximum unit scale [MW]	1,700	1,660	98% (red)	Direction of search	Limits to the economies of scale [110]
	Construction time Fig. 8	Increase in construction time [months]	58 (1970-74)	107 (2014-18)	84% (red)	Legitimation, entrepreneurial experimentation, market formation	No improvement through learning-by-doing [109]
Context: TIS-context relationships	Competition in non-fossil power generation	% of non-nuclear in total non-fossil power generation [TWh]	8’906	6’270	71% (orange)	Market formation, direction of search	Other non-fossil technologies tend to have higher relative advantage [3]

[*] $\frac{\textit{1970s value} - - \textit{Current value}}{\textit{1970s value}} = 1 - - \frac{\textit{Current value}}{\textit{1970s value}}$, **going from 0 if current value is equivalent to the 1970s up to 1 if the current value is zero.**

[**] Assuming the optimistic scenario under which capacity installed would still grow 100GW by doubling the capacity installed in Asia (+50GW) and by conceiding a similar capacity addition in other regions (+50GW).

[***] Communities are defined as hubs of densely connected nodes. In our network we find 12 communities in the 1970s and 9 communities in the 2010s. In the 1970s, 3 components have 3 actors or less, i.e., substracting 3, and in the 2010s, 6 components have 3 nodes or less, i.e., substracting 6.

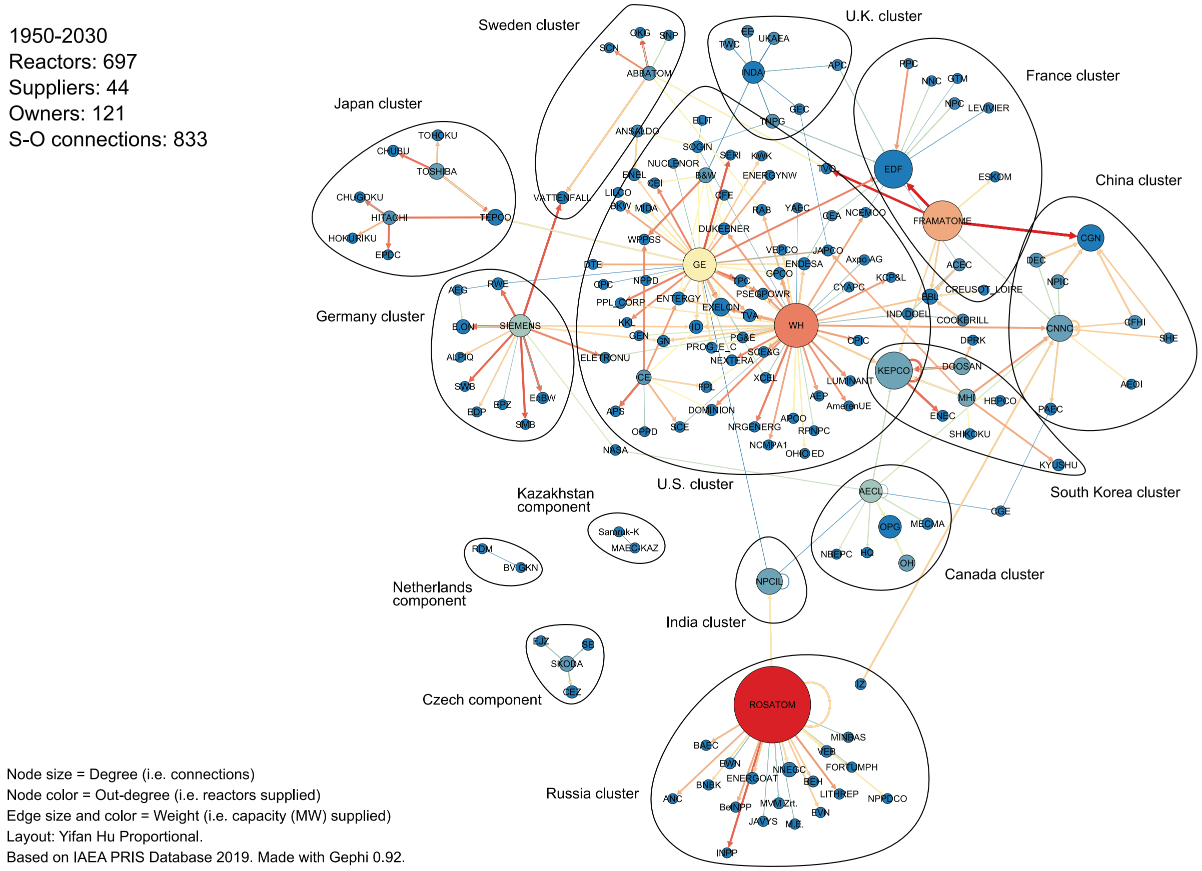

Fig. 13. Historical network of supplier-owner relationships and national clusters.

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