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Time is money, but sometimes it costs more: an economic history perspective into nuclear projects' pitfalls

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ABSTRACT
The changing socio-economic context has a crucial impact in nuclear decisions and execution of the projects. The nuclear projects initiated over the past 20 years reduced their construction times relative to those initiated before. Of the over 600 the nuclear projects built over the past 70 years only 3% took longer than 15 years to complete. Analysing the lengthiest projects within their economic context, reveals that 'when and where', (i.e., the contextual risks) explains most the delays, thus questioning whether nuclear power plant projects are inherently examples of the megaproject 'pathologies.' The analysis of the lengthiest nuclear power projects makes evident that the failure to deliver nuclear plants on time and within budget was related to the historical period and/or the specific location more than to any inherent characteristics of nuclear power plants. Stakeholders of nuclear projects (and megaprojects in general) should be attentive to socio-economic changes and macro-economic impacts to avoid pitfalls.

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Socio-economic context; macroeconomic risk; financial costs; managing uncertainty

1. Introduction

Megaprojects are endeavours characterized by large investment commitment, vast complexity (especially in organizational terms), and long-lasting impact on the economy, the environment, and society (Brookes and Locatelli 2015). Given their long- execution times, megaprojects face high uncertainties which may result in costs way beyond what was initially planned. Two frames have been used to interpret this reality (Lehtonen 2021). The mainstream rationalist framing argues that megaprojects suffer from inherent 'pathologies' (e.g., Gunton 2003) or 'pitfalls' (Priemus 2010), where success is so rare that it can be studied only as small-sample research (Flyvbjerg 2014). The alternative framing recognizes the complexity and uncertainty faced by

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megaprojects but is reluctant to accept the universality of megaproject failures, among other things because the metrics for failure/success in megaprojects often extend beyond the specific project (Lehtonen 2021). Accordingly, the alternative view focuses on the contextual risks rather than on the fundamental essence of the megaprojects as the main causes for their poor performance (when/if it occurs). This opens the possibility for other interpretations and ultimately calls into question the very notion of 'pathology' (van Marrewijk et al. 2008; Benjamin and Greene 2009; Sanderson 2012; Dimitriou, Ward, and Wright 2017; Lehtonen, Joly, and Aparicio 2017; Lehtonen 2019).

Nuclear power plants are megaprojects. The question this paper address is whether the hypothesis that emanates from the rationalist view holds for nuclear plants: can they be expected to run over scheduled time and over budget, consistently and pathologically, independently of when and where they are built? In this essay, I approach the question utilising the tools of economic history. Methodologically this implies a meticulous knowledge of the chronology of events leading up to and during the project construction, given that historical causality runs one way: what happened during the project, cannot be caused by something that happened after it. The methodology also calls for dynamic analysis of change. If something does not change, it is unlikely that it will have any impact on the variables that do change. One of the roles of economic history is to focus attention on the economic factors that influenced the development of issues that are essentially non-economic in character. In this case building a nuclear power plant is essentially an engineering issue, which, this paper argues, is impacted by multiple economic variables. The effects of economic causes constitute only one aspect of a many-sided phenomenon. The full story surely lies beyond the competence of an economic historian.

This article examines nuclear pitfalls in their historical context. Given that observable, systematic, and comparable indicators of the 'iron triangle' criteria of project performance (cost, timetable, and predefined project prescriptions) do not exist for the over 600 commercial reactors built in the world over the past seventy years, the lead time is used as a proxy. By convention in the nuclear industry, the lead time is typically measured from the first day of pouring of concrete for the foundation of the plant to the day first commercial operation (which is usually 'declared' after test operations have been completed) (IEA 2019).

Time is money, but not all time periods cost the same. In nuclear projects, the length of time between the initiation of construction activities and the start of commercial operation is the most expensive, and as such this period is a key variable to assess performance. This is discussed in the first section. The second section makes use of the Power Reactor Information System (PRIS) database of the International Atomic Energy Agency (IAEA) to analyse the spread of the lead times for all commercial reactors successfully built from the 1950s to 2020 by year of starting construction and by reactor manufacturer, differentiating domestic builds from reactors built abroad. This analysis allows for a challenge to the observation by Flyvbjerg (2014) that 'performance in megaproject management is strikingly poor and has not improved for the 70-year period for which comparable data are available' for the case of civil nuclear power plants. The quantitative and qualitative analysis shows that the statement of Flyvbjerg does not hold for nuclear projects. If project management had not improved over time, the performance in this class of projects would have continued to be poor. However, the spread of the construction times for nuclear projects has been reduced over the past 20 years, and only a small sample belongs to cancelled projects and those that took longer than 15 years to be completed. Section three concentrates on the 19 reactors that took more than 15 years to complete, over the past 70 years. Each project is examined within its economic context. This reveals that 'when and where' (i.e., the contextual risks) can explain a great deal of the pitfalls. The analysis points to the fact that the failure to deliver nuclear plants on time and within budget was related to the historical period and/or the specific location more than to any inherent characteristics of nuclear power plants.

2. Time is money, but some 'times' are more expensive than others

Ideally, to be able to assess the performance of nuclear power plant construction projects would require systematic and comparable indicators for the 'iron triangle' criteria of project performance. These are cost, timetable, and predefined project prescriptions (Dimitriou, Ward, and Wright 2017). Then, and only then, could deviations from the initial plans be evaluated and the project's implementation quality be considered. Such data do not exist for the over 600 commercial reactors built in the world over the past seventy years. The literature on the costs of nuclear power plants typically considers overnight costs, adding up the costs as if the plants could be constructed overnight (Berthelemy and Rangel 2015; Lovering, Yip, and Nordhaus 2016; Grübler 2010). This effectively excludes the most important costs of nuclear projects: the financing costs and the interest accumulating during the construction period. Figure 1 provides a stylised view of the costs of a nuclear power plant over time. The construction period accounts for the largest costs, not only because of the costs of the actual materials and labour in the construction, but also because of the costs of financing the upfront expenses. Nuclear cost overruns have been found to be heavily influenced by interest costs and time overruns (Sovacool, Nugent, and Gilbert 2014; Sovacool,

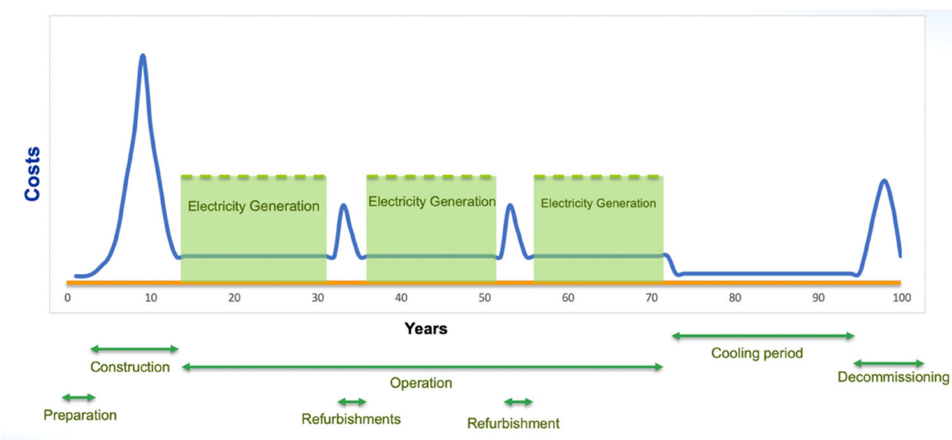

Figure 1. Stylised costs schedule of a nuclear power plant.
Source: elaborated from IEA materials.

Gilbert, and Nugent 2014a, 2014b). The World Nuclear Association (2017, 3) recognizes that 'the economics of new nuclear plants are heavily influenced by their capital cost. Interest rates and the length of the construction period are important variables for determining the overall cost of of capital'. Given the economics of nuclear new-build's sensitivity to the cost of capital, it is crucial that project developers secure as low a cost of capital as they possibly can.

Attempts have been made to include the financing costs in evaluations of nuclear projects' performance over time (Portugal-Pereira et al. 2018), but to estimate the financing costs, these studies have had to use the average discount rate for nuclear power generation projects. This flat rate estimate ignores the modifications of financing costs over time and across projects.

Crucially, capital costs differ according to the kind of promoter of the nuclear project and the nature of funding they have access to. Public investors (say governments or state-owned companies) can borrow money at lower interest rates than private actors (D'haeseleer, 2012). Besides cheaper financing costs, public funding also tends to offer other crucial advantages such as longer grace and repayment periods. Take the example of the Export Import Bank of the United States (Eximbank), the public bank which provides assistance to US exporters, which financed most of world's nuclear projects sold internationally from 1965 to 1985 (Rubio-Varas and De la Torre 2016; Rubio-Varas, De la Torre, and Connors 2021). While the average payment period for an Eximbank loan was 8 to 10 years, for nuclear loans the usual repayment period was 18 to 20 years (Holiday, 1981). This included grace periods of up to 9 years. Private sector funding expects repayment to begin shortly after the loan is granted (grace periods are rarely extended beyond a year) and to obtain full reimbursement within 5 to 10 years of initial lending. Both public and private funding, despite their different costs, are equally subject to overall variations in the interest rates (that is the costs of borrowing money) because of fluctuations in economies in which the borrowing takes place, and because insuring against it (such as taking fixed interest rate loans) tends to be prohibitively expensive.

When interest rates are high, projects with high initial capital costs, such as nuclear power plants, are disadvantaged in comparative financial appraisals relative to alternative technologies to produce electricity that enjoy shorter lead times and require smaller up-front investments. The historical analysis of the evolution of the interest rates for funding nuclear power plants projects reveals that before the end of the 1970s, real interest rates remained very low, thus making nuclear projects attractive even for the private sector as much as for many governments. An escalation of real interest rates began from the mid-1970s, in the middle of the oil crisis, in the US and Germany, though it took until the mid-1980s to reach France and the UK. No private nuclear project could be competitive at the very high interest rates of the early 1980s. It is therefore unsurprising that the so called 'nuclear renaissance' proclaimed at the beginning of the 21st century coincided with the return to real interest rates below 5 per cent (in the US, the UK and France, although not in Germany) (Rubio-Varas, De la Torre, and Connors 2021). Figure 2 puts side by side the costs of financing and the new nuclear projects initiated each year from the 1950s to 2013. Observe how most nuclear projects started construction when the financing cost were below 2 per cent

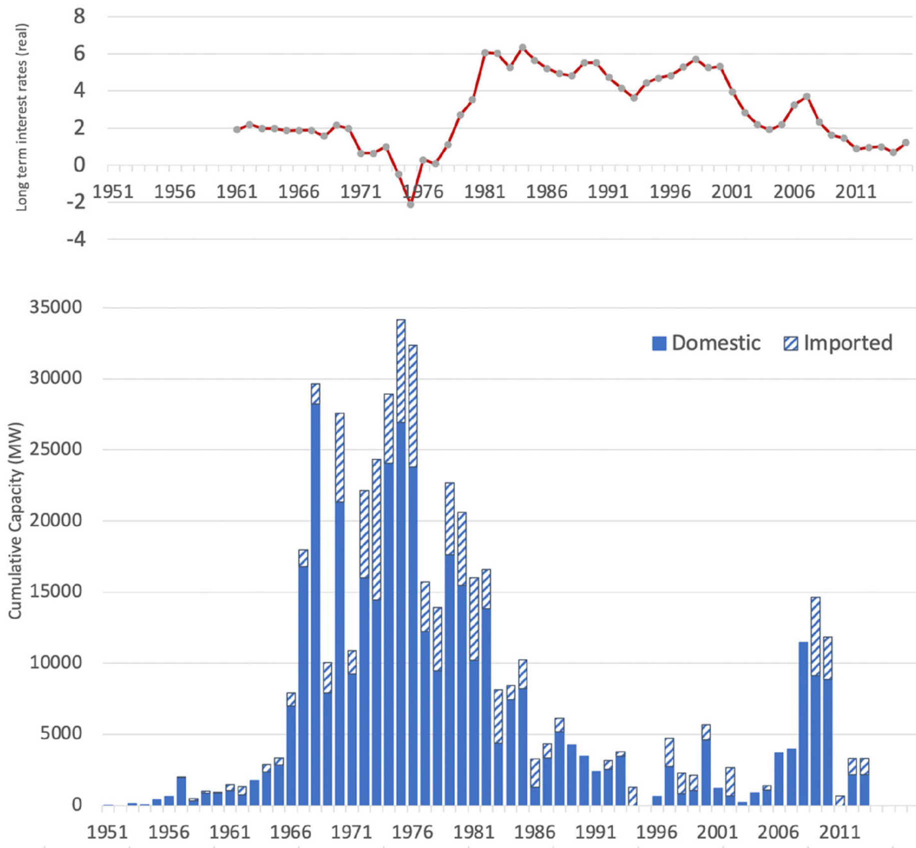

Figure 2. Financing costs vs new nuclear projects initiated yearly 1950–2013.
Sources and notes: Own elaboration from the compilation of the IAEA PRIS databases. The year refers to the construction start. Completed reactors only, thus those connected by 2020 began construction in 2013 at the latest. Domestic built refers to those projects where the reactor manufacturing takes place in the country in which the reactor is located. Imported reactor denotes a reactor coming from a different country where it is located. World Development Indicators, World Bank for real interest rates (blended for the US, Japan, the UK and France). Note that real interest rate is the lending interest rate adjusted for inflation. Rates are representative interest rates offered by banks to resident customers. A negative real interest rate indicates a loss in the purchasing power of the principal as inflation was above the nominal interest rate.

(in real terms) and very few new builds occurred after the rise in interest rates from the late 1970s. Nuclear construction timidly returned when interest rates fell again in the early 2000s. Figure 2 also makes evident that most of the commercial reactors have historically been domestically built (466 out of 628 reactors) in countries that have had the manufacturing capacity to do so (see Rubio-Varas, De la Torre, and Connors (2021) and Figure 3). The 628 reactors that were connected to the grid, listed in the PRIS database, were manufactured by companies from 12 countries. However, construction was dominated by three nations: the US, Soviet Union/Russia, and France, which together built more than half of the reactors listed in the database.

It is worth noticing that together with the rise of interest rates, the late 1970s brought other important macro-economic changes: the second oil crisis, in 1979, hardened the world's economic outlook and ushered in a definitive change in energy policy as efforts concentrated on reducing energy consumption. The uncertainties over

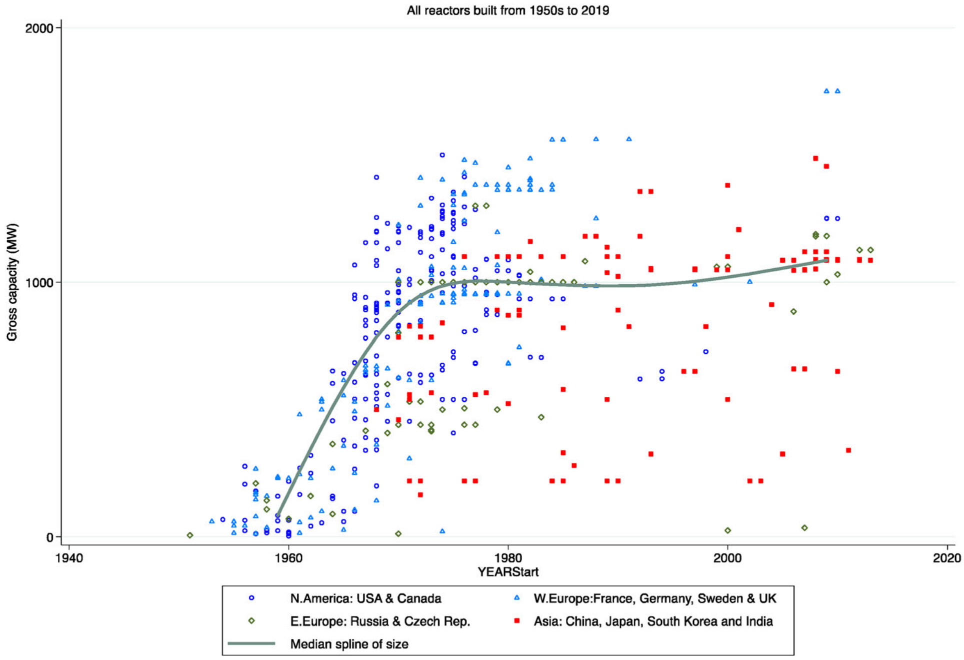

Figure 3. Reactors by size and region of the manufacturer.
Source and notes: own elaboration consolidating IAEA-PRIS databases. The year refers to the construction start. The median spline of the size of the reactors calculates cross medians and then uses the cross medians as knots (5 in this case) to fit a cubic spline. This is a widely used statistical smoothing tool.

the world economy translated into falling energy consumption in many countries. The 1980s also brought the onset of neoliberalism, which affected, to varying degrees, the economic role of the state across the Western world. Until that date, financing by the supplier's government had been more important to customers than the overall cost evaluation of the project. For exports of nuclear reactors, this had been crucial. In fact, the US government financed, through the Export-import bank, more than half of the world's international sales of nuclear reactors outside the Soviet bloc. This explains a great deal of the US supremacy in the global nuclear market before the 1980s. Eventually, competing suppliers of nuclear reactors found support from their respective public financing institutions to finance the export of nuclear power projects. With the onset of neoliberalism, the number of nations willing to support the exports of nuclear technology and services with public money declined. In fact, the financial facilities provided by the historically largest exporter of nuclear reactors, the US, came to an end by 1985, and this marked the end of the US exports of nuclear reactors (Rubio-Varas and De la Torre 2016).

This issue also affected the kind of nuclear power plants that got built and by whom, and how this changed over time. On the first issue, Figure 3 shows that reactors got larger over time. Nuclear technology was developed by the countries with the largest electricity demands in the world (the US, the USSR, Canada, and France) and they steadily increased the reactor size from a few hundred MWe in the early 1960s to above 1000Mwe by the late 1970s. This in fact left behind many nations with smaller electricity markets, which could not accommodate the large standard reactor that the manufacturers supplied (Rubio-Varas, De la Torre, and Connors 2021).

The nuclear power industry in the West in the early 1980s faced the perfect storm: increasing financial costs, less support from the state, together with slower electricity demand growth and the emergence of green parties (all of then antinuclear at the time). Figure 3 shows the switch from West to East in the manufacturing of nuclear reactors that has taken place since the 1980s. In fact, two thirds of the nuclear projects whose construction began after 2000 took place in China and Russia, where the costs of financing depend on their government's ability to raise money rather than on market interest rates. In these countries, the government undertakes the projects, electricity demand continues to soar, and public opinion has little chance to interfere with government plans.

We can infer from the forgone paragraphs that time is money in nuclear projects, but not all the time intervals are equally expensive. The construction period is the most expensive. Most megaprojects do not produce any revenue until completion and delays become the commonest path to non-viability. As delays accumulate, so does the debt. The combination of escalating construction costs, delays, and increasing interest payments renders a project unviable, by making it impossible for the income from a project, when it finally arrives, to cover costs. Yet, we have seen that different forms of ownership of nuclear projects define the type of debt financing and have varied across different periods of history. Thus, the risk of non-viability varied across location and decades. A year of delay for a publicly owned utility building a nuclear power plant in the 1960s would have cost far less than the same delay for a private company implementing a nuclear project in the 1990s. The former faced lower financing costs than the latter, and the overrun costs were significantly less important.

Besides the debt trap, delays have a crucial role in extending the time horizon that needs to be forecasted. The longer the period ahead in which the project must be developed, the more difficult it is to offer a comprehensive forecasting and an appropriate contingency plan about the possible changes in the societal, economic, and policy context. Consequently, a delayed project is more likely to suffer further unforeseen delays and cost increases.

3. Completion times through history

The length of time between the start of construction and the start of commercial operation is the dearest, and as such a key variable to assess performance. In the absence of information on actual spending and predefined project objectives, lead times are the only observable, systematic and comparable metric for an overall comparison of nuclear projects' performance. By convention, in the nuclear industry the lead time is typically measured from the first day of pouring of concrete for the foundation of the plant until the first day of commercial operation (which is usually 'declared' after test operations have been completed) (IEA 2019).

Lead time has been an object of study but, even in the more economically minded papers, the studies tend to be contextless. In particular, the question of 'when', that is, the historical period in which the project was built is seldom considered (see for

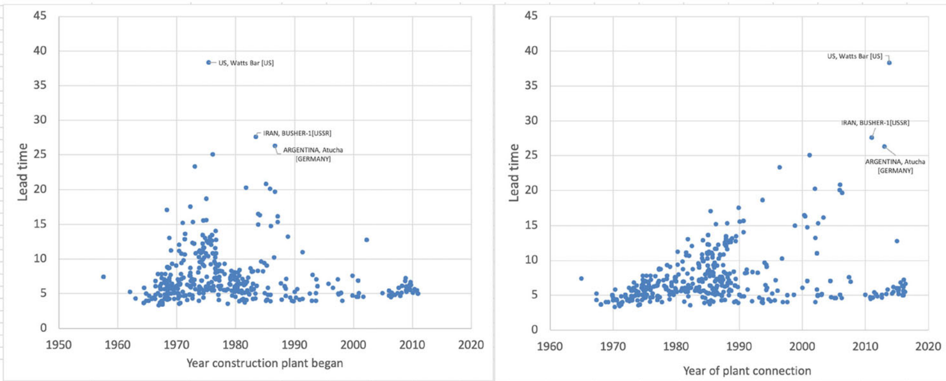

Figure 4. Historical vs presentist view of the lead times of built reactors starting construction date vs connection date (1951–2013).

Sources and notes: Own elaboration from the consolidated IAEA-PRIS database that includes the world's all commercial reactors connected to the grid (including those that have been shut down), consisting of a total of 628 reactors. For the three largest outliers the country where the reactor was built, the name of the plant and the nationality of the reactor manufacturer (in between square brackets) are indicated. Note that the lead times are identical in both figures.

example Benson (2020) and Carajilescov and Moreira (2011) and the references therein), or it is considered only marginally (Csereklyei et al. 2016). The precision about the context is important because the causes behind abnormally long lead times are heterogeneous both across time and across space. Therefore, one needs to observe nuclear plant lead times within their specific historical context.

To obtain a first impression about the historical evolution of nuclear lead times, Figure 4 presents two alternative representations of the lead times of commercial nuclear reactors. The first image uses a historical perspective, plotting the lead time against the year in which the construction began in each case. The second reflects the presentist perspective, plotting the lead time against the year in which the plants were connected to the grid. In both cases the lead times are identical. Only the perspective changes, but this leads to different interpretations. The foremost notable feature of the historical approach is that it shows the virtual disappearance of outliers from 1987 - no reactor whose construction began after that date took an abnormally long time to build, only two taking longer than 10 years. On the contrary, the presentist perspective leads Portugal-Pereira et al. (2018) to claim that there has been 'a two-fold increase in lead-time in the last 40 years.' However, the latter perspective overlooks how the building of nuclear power plants has evolved over time, treating old and new projects as equal, as if their individual histories did not matter.

The presentist view also misses the impact that the increasing the size of the reactors had in increasing the cost per kWh as it led to longer construction times during the late 1960s and early 1970s – which could be described as the learning-by-doing period – thus offsetting the expected cost savings (Cooper 2010; Krautmann and Solow 1988). This is a phenomenon common to energy technologies in general (Madureira 2014). Reactor size stopped growing from the 1980s as shown in Figure 3. The plants that began construction after Chernobyl have had reasonably short lead times, while most of those that were under construction at the time of the accident suffered delays. It is true that fewer projects were initiated after 1986, but progress in reducing led times can be observed over time when taking an historical perspective, which the presentist view overlooks. This progress may be attributed to the fact that most reactors whose construction began from the late 1980s have been built in Asian countries. In more centrally-planned and vertically integrated power systems, such as those in China, South Korea and Japan, the lead time is known to be shorter (Portugal-Pereira et al. 2018) than in Europe and the USA, which dominated nuclear construction before the 1980s.

All in all, if lead time were to be used as a measure of success, of the nuclear reactors ever connected to the grid (between 1951 and 2020), 84% took less than 9 years to build, while only 3% took longer than 15 years. Long lead times seem to be the exception rather than the rule in completed nuclear projects. This is true for both the historical and the presentist perspective since the lead times are identical in both. This evidence seems to contradict the statement that nuclear power plant projects are inherently examples of the megaproject ‘pathologies’ (e.g., Gunton 2003) or ‘pitfalls’ (Priemus 2010), where success is so rare that it can be studied only as small-sample research (Flyvbjerg 2014).

Yet, Figure 4 shows only the reactors eventually connected. Thus, even if a vast majority of the commercial nuclear reactors that have been operational in the world were connected within 9 years of construction start, are the reactors in Figure 4 a small sample of all the reactors ever started? Does the story change if we consider the projects that were abandoned before completion? The Power Reactor Information System (PRIS) database of the International Atomic Energy Agency (IAEA) partially helps to provide a satisfactory answer, since it reports data on all reactors around the world, including those currently under construction, under planning, cancelled or suspended as of 2021, or abandoned or suspended before construction start. Unfortunately, the database does not provide dates for the construction start for uncompleted reactors, although for some countries it is available from alternative sources. However, it is possible to compare the total nuclear capacity that has been built versus the planned nuclear capacity that failed to complete. For

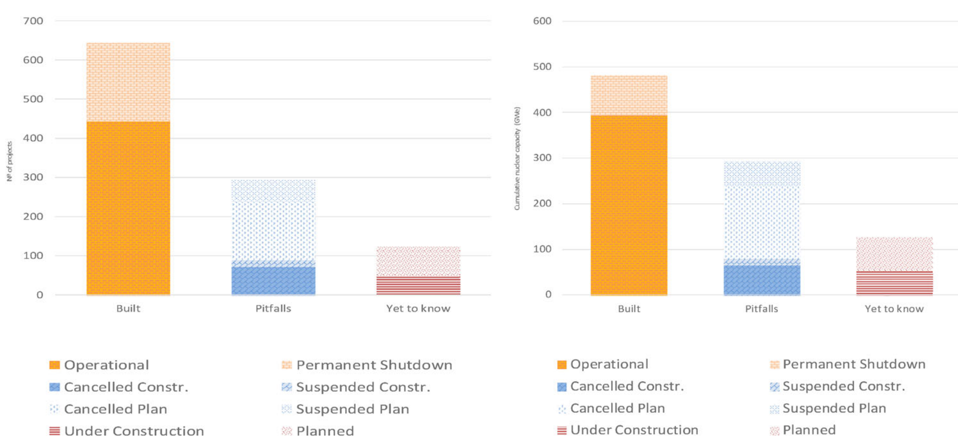

Figure 5. Comparative N° of projects and accumulated nuclear capacity: connected vs abandoned (1951–2020).

comprehensiveness, Figure 5 also includes the number of projects and the cumulated capacity whose fate we do not yet know with certainty (reactors under construction, planned or being considered as of March 2021).

All in all, Figure 5 shows that the small sample actually belongs to the cancelled nuclear projects, which together with suspended construction plans can be considered as those that truly suffer from pitfalls (a total of 90 nuclear projects were cancelled or suspended after construction began, 12% of all ever undertaken). Over half (52%) of the cumulative capacity classified as suffering from pitfalls, in Figure 5, belong to nuclear projects in the USA. All forty-two unfinished projects in the USA were initiated during the 1970s, as were all the cancelled projects in Spain (2.5%) and Italy (3.3%), all of which can be explained by the economic context of declining electricity demand and soaring interest rates, which made nuclear projects redundant and impossible to finance successfully at the time (Rubio-Varas, De la Torre, and Connors 2021). A quarter of the abandoned projects in Figure 5 (24%) belong to nuclear projects in the former USSR, most of which were also initiated in the late 1970s and the first half of the 1980s, but whose abandonment can probably be attributed to the Chernobyl disaster and the subsequent dissolution of the Soviet Union.

4. Understanding the context of the 19 lengthiest nuclear projects ever undertaken

Now that we have established that most of the nuclear reactor projects ever started were indeed completed (to be precise, 88% of all reactors that began construction were eventually connected to the grid), let us return to the outliers in Figure 4. In order to investigate whether they have identifiable common traits, which could be linked to their economic context, Table 1 lists the 19 rectors that took more than

Table 1. The 19 lengthiest nuclear projects ever completed (1950s–2020).

Starting construction year	Years to completion	Plant location	Reactor name	Reactor's manufacturer nationallity
1973	43	USA	WATTS BAR-2	USA
1975	36	IRAN,ISL.REP	BUSHEHR-1	GERMANY /RUSSIA*
1981	33	ARGENTINA	ATUCHA-2	GERMANY
1983	27	RUSSIA	ROSTOV-2	USSR /RUSSIA
1986	25	RUSSIA	KALININ-4	USSR /RUSSIA
1983	24	ROMANIA	CERNAVODA-2	CANADA
1976	24	BRAZIL	ANGRA-2	GERMANY
1973	23	USA	WATTS BAR-1	USA
1981	20	RUSSIA	ROSTOV-1	USSR /RUSSIA
1965	20	UK	DUNGENESS B-2	UK
1985	19	RUSSIA	KALININ-3	USSR /RUSSIA
1985	19	UKRAINE	KHMELNITSKY-2	USSR /RUSSIA
1974	19	USA	COMANCHE PEAK-2	USA
1986	18	UKRAINE	ROVNO-4	USSR /RUSSIA
1965	18	UK	DUNGENESS B-1	UK
1977	17	MEXICO	LAGUNA VERDE-2	USA
1983	16	SLOVAKIA	MOCHOVCE-2	CZECH REP.
1968	16	USA	DIABLO CANYON-1	USA
1974	16	USA	COMANCHE PEAK-1	USA

Source and notes: Own elaboration from the consolidated IAEA-PRIS database consulted in March 2021.
*The original agreement for Bushehr-1 was with the German KWU. When construction restarted in 1996, it was with a Russian reactor after the refusal of the Germans.

15 years to complete construction. In this article, we do not distinguish between projects according to their technical characteristics, because it is in the socio-economic context of each project that we are interested rather than the respective qualities of competing designs. It is worth noting that the reactors in Table 1 tend to be large, but not extremely large (on average 970 MWe). Pressurised Water Reactors (PWRs) are slightly overrepresented in the sample, accounting for 14 out of the 19, given that just over 55% of the connected reactors in the world are PWRs. As the USA and the USSR have historically been the largest manufacturers of nuclear reactors, it comes as no surprise that the list of the slowest ever nuclear projects to be completed is dominated by reactors of American or Soviet manufacture (13 of the 19 lengthiest projects). All had construction start between 1965 and 1986, with the pitfall-suffering reactors geographically distributed in an interesting manner over decades: while all slow projects in the USA happened to start construction before 1974, the construction of all of the slow projects in the Soviet bloc took place after 1981. As an economic historian, I can only interpret this as showing that the USA projects suffered from having to traverse the macroeconomic instability that started with Nixon's decision to leave the Bretton Wood system in 1972, and the huge industrial crisis brought about by the oil crisis, while the Soviet projects struggled because of the collapse of the Soviet Union. Let us now examine the context for each of these 19 nuclear reactors.

On the list of long construction times in Table 1, all imported reactor projects were located in countries that endured severe economic and institutional crises while the projects were underway, which significantly extended the construction times. To be precise the three Latin American lengthy nuclear projects (in Argentina, Brazil, and Mexico) happen to coincide with the most severe economic crisis in the region in decades - the debt crisis of the 1980s - which Ocampo (2014) called the 'the most traumatic economic event in Latin America's economic history' - with the end of military dictatorships, and, in Argentina (1983) and Brazil (1985) the beginning of an unstable period of democratisation (see O'Donell 1988). The national situation of economic crisis created severe financial problems for these projects according to the IAEA (2008). Similarly, the Iranian revolution suspended the plan of Busheher-1 in 1979, which was only restarted in 1996, when the Germans were substituted by Russians as the technological supplier (Kịbaroğlu 2007), in the midst of the conflict over the Iranian nuclear programme still ongoing today.

One may expect more uncertainty in building nuclear projects abroad, if only because additional stakeholders are involved in the decision-making, regulation and complex logistics that involve the transport of immense technological artefacts across oceans, over thousands of kilometres. However, most (11 out of 19) of the slow-to-complete projects in Table 1 are domestic projects rather than reactors built abroad, and they tend to come in pairs (two reactors at the same site) in both East and West.

The decomposition the Soviet Union has its own place in this list of the lengthiest nuclear projects ever completed, as the USSR was involved in 8 of the 19 projects in Table 1, all of whose construction began between 1981 and 1986. The economic crisis generated by the dissolution of the Soviet Union is difficult to exaggerate. For our purposes, it suffices to mention that the annual growth rate of electricity demand turned negative across the Soviet bloc - that is, the electricity consumption declined year by year – for the first half of the 1990s. On the one hand, the redrawing of the map in Eastern Europe generated a number of nuclear power plant projects that began as 'domestic' but ended up as 'imported' reactors across Eastern Europe and the ex-soviet republics. The traumatic end of Ceausescu's regime in Romania suspended the construction of Cernavoda-2 in 1990, which was resumed only in 2001 (Alessandrini 1998). The dissolution of Czechoslovakia took effect in January 1993, and for the lack of funds, the new Slovakian government suspended the construction of the Mochovce-2 reactor in March 1993, restarting construction only once new financial arrangements were secured in 1996 (Valach 2001).

Ukraine will forever be associated to the disaster of Chernobyl in 1986. At the time of the accident, 10 reactors of Soviet manufacture operated on the Ukrainian territory, 7 others were under construction (including units 5 and 6 at Chernobyl, whose construction was cancelled) (Kasperski 2018). Three of the reactors under construction (Zporozhhye units 4 and 5, and South Ukraine 3) were completed before the moratorium on nuclear construction in Ukraine in 1990. Two other reactors - Khmelnistski-2 and Rovno-4, known as the 'K2/R4' - made it to the list of the lengthiest nuclear projects after having been affected first by the nuclear moratorium and then by the independence of Ukraine in 1991. By the time the moratorium was lifted in 1993, Ukraine was a politically independent nation, although still dependent on Russia for nuclear technology, fuel and services. The country was facing severe economic difficulties, alongside ongoing international negotiations relating to Chernobyl's consequences and compensations. The K2/R4 become part of a deal to resolve the negotiations. The European Bank for Reconstruction and Development (EBRD) and Euratom earmarked, respectively, $215 million and $585 million for Ukraine, subject to a number of conditions including the upgrade of K2/R4 to safety standards comparable to Western nuclear plants of the same generation (Council of Europe Assembly 2001; Surrey and Thomas 1999). It was a difficult deal to be accepted both in the West - where many questioned the soundness of the deal on safety, electricity needs and financial grounds (Surrey and Thomas 1999) - and in Ukraine, which continued to request additional discussions on certain loan conditions that the country considered impossible to comply with right up until 2001 when they evenually refused to sign the EBRD loan contract. By 2004 the two reactors were finally connected by Energoatom – Ukraine's public nuclear power utility – with the help of a consortium of the French firm Framatome ANP and the Russian firm Atomstroyexport.

Continuing with the Soviet saga, the four reactors in Russia on the list of lengthiest nuclear projects belong in fact to two different nuclear power plants: Rostov and Kalinin. Though it is more difficult to track the financial and economic constrains in the Russian case, the IAEA (1999) attributed the delays in both plants to (1) rapid decline of investment volumes, (2) more stringent safety requirements [post Chernobyl], and (3) ecological and public expertise (possibly referring to the protests against Rostov (NTI 2008)). In fact, both projects were mothballed in 1990 (Nuclear Engineering International 2010). It could be safely assumed that they followed the same path as other nuclear projects in the ex-Soviet Union described above, caught by the institutional turmoil, the economic crunch, the decline of electricity demand, and the financial problems associated with the decomposition of the Soviet Union.

In a report on the lessons learned in nuclear project construction, the World Nuclear Association (2018, 6) states that 'the risk of delay and budget overrun are especially significant in first-of-a kind (FOAK) engineering projects'. Nonetheless, on the list of the slowest nuclear projects in Table 1 there is only one truly FOAK project: the two reactors at Dungeness B, on the south coast of England, which were the first commercial Advanced Gas-cooled reactors to begin being constructed in the UK. Taylor (2016) concludes that the largely unchecked power of the British nuclear establishment was key to the failure of its nuclear ambitions. But the business and management side played a large role too. The wish for competition in design and speedy construction led to poor and hasty designs. The consortia began construction too soon, and design problems meant that work started had to be redone, costs escalated, and several companies collapsed (as early as 1969 the main contractor, APC, ceased trading) (Deaton 2009; Wearne 2015). Furthermore, the British economy was also hurt by a profound economic crisis during the 1970s – according to Morgan (2017), 'the 1970s have gone down as the dark ages, Britain's gloomiest period since the second world war'. Given that the UK nuclear industry was fully state-led, it comes as no surprise that the longest completion times of British nuclear reactors belong to those constructed in the 1970s - from Dugeness B to Heysam A. In other words, every British reactor finished before 1971 or begun after 1980 took less time to build than those whose construction overlaps with the period 1971–1979. It is not heroic to assume that the economic context of the 1970s had an impact on the construction times of the British nuclear industry.

Five of the 19 slower to build reactors in Table 1 belong to the United States, including the longest ever reported nuclear project to be completed: Watts Bar unit 1, which took officially 43 years to be completed. The costs and delays of US nuclear power plants has been widely discussed in the academic literature (Komanoff 1981; Koomey and Hultman 2007; Cohn 1997) as well as in reports by contemporary institutions such as the US Congress. In February 1979, just weeks before the Three Mile Island accident, the Congressional Budget Office of the United States Congress made public a background paper on the delays of nuclear reactor licensing and construction (CBO 1979). The report identified three major sources of delay: economic factors (adding an extra year or more), changing regulations (about six months extra) and public participation in licencing (another six months). The report further stated: 'the longest delays occurred because of unanticipated declines in the demand for electrical power or difficulty in raising financing for a reactor project [...] Most of these delays occur after licensing [...] Financial delays appear to be more related to financial problems of electric utilities in general [...] than to uncertainties created by the nuclear regulatory process' [...] sources of more minor delays are state/federal redundancy in license review, management problems in construction, and labor disputes. Taken together, these factors typically account for only a few months delay in reactor lead time, but any one has the potential of causing considerable delay' in the reactors sampled by the CBO study (CBO 1979, x-xi).

Yet, all three USA plants on the list of the slowest nuclear plants to be ever built (Diablo Canyon, Watts Bar 1&2 and Comanche Peak 1&2) suffered apparently from different types of delays accumulated over the years, even if the literature about these plants is surprisingly scarce. Diablo Canyon asked for its first building extension already back in 1974 due to labour unrests and strikes (US-NCR 1974). Then by 1979, with the plant almost completed, the fuel loading was delayed by the requests for a second seismological evaluation by the NCR (CBO 1979). But still in 1981 protests at the door of the plant further delayed its opening which finally happened in 1984. The delays in the building of Watts Bar and Commanche Peak nuclear power plants could, at first sight, be attributed to new regulation introduced during the 1970s, which increased costs. A closer inspection of both cases ultimately links back to the delays imposed by the regulator requirements relating to earlier mistakes in the design and execution of the projects at the industrial end (US-NCR (2021) and Posey (1987)). These delays elongated the projects beyond the initial timeframe rendering the original plans and calculations useless in the new socio-economic context of a decade or more after the construction began.

Interestingly, little academic work has been dedicated to any of these American nuclear projects plagued by pitfalls or to other projects which were derailed in a different fashion (for instance, the Zimmer nuclear plant in Cincinnati, Ohio, was 97 percent complete in 1984 when it was converted to a coal-fired plant because its safety and quality could not be proven; see McClanahan 2019). A better understanding of the socio-economic and business context of each of these projects may give a new perspective to the issue of nuclear project overrun.

5. Concluding remarks

This article contributes to the understanding of the ways in which nuclear projects emerged, evolved and, in some cases, failed, within their historical socio-economic context. The vast majority of nuclear projects built were completed in under 9 years, only 3% took abnormally long to build (more than 15 years). If the mainstream interpretation of megaproject problems were right, most nuclear power plants would have taken exceptionally long time to be completed, and no improvement would have occurred over time. This article finds that the plants that have taken the longest to construct would not have been built faster no matter how much operational control was exercised over the project, simply because the evolution of its contextual and historically shaped circumstances were impossible to forecast. Rationalists may argue that those projects should never have started, but that could not be known with the information that was available beforehand.

The longer the time into the future, the more numerous are the variables that may spin out of the forecasted path. Forecasting a decade from now is increasingly difficult in a world under acceleration. Besides anticipating the possible impacts of different macroeconomic scenarios, including the alterations to commodity markets and labour costs, the planner will also need to estimate the plausible impacts of the changes that the evolution of competing technologies and that geopolitical shifts may produce. Furthermore, for producing a comprehensive forecasting and appropriate contingency plans, the investor on a nuclear project also needs to understand the micro-level vicissitudes at the subnational or even local level that will affect a variety of stakeholders with totally different interests, which may vary along the way. The required extended chain of communication, with slow and contradictory feedbacks, might lead to conflicts and dispute, thus affecting the project in the context of delay and cost overrun.

There is no reason to believe that in the future, socio-economic and political variables will be easier to predict. Project managers and key stakeholders of nuclear projects (and megaprojects in general) should be attentive to potential future socio-economic changes as a risk and challenge to successful completion of the project.

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