Global Divergence in Nuclear Power Plant Construction:

the role of political decentralization

Andrew G. Benson

Department of Economics
3151 Social Science Plaza A
University of California, Irvine
Irvine, CA 92697-5100

Email: agbenson@uci.edu

Website: `https://sites.uci.edu/agbenson/`

Number of pages:	79
Number of tables:	4
Number of figures:	4

Abstract

Lead time—the duration of construction and commissioning—is an important determinant of the capital cost of nuclear power plants (NPPs). For an industry dominated by a handful of multinational firms, the degree of cross-national variation is surprising. NPP lead times have historically trended upwards over time in Western nations, and yet they are comparatively quick and stable in East Asia. I theorize that the institutional capacity and autonomy of subnational governments can partially explain these patterns in the data. Having assembled a novel dataset on the design specification of the global population of NPPs, I empirically document an association between political decentralization and longer NPP lead times that is not explained by cross-country differences in NPP design. The estimated effects imply that one standard-deviation increase in a nation's political decentralization is associated with roughly a 9% increase in lead time, *ceteris paribus*. Furthermore, I investigate whether decentralization interacts with previously theorized explanations for poor NPP construction economics. I find that the penalty to lead time that arises from greater levels of project scale and complexity is sharpest in politically decentralized nations. I also find that "forgetting-by-doing"—worsening project performance with the accumulation of experience—is present in highly politically decentralized nations but absent elsewhere.

Keywords — economics, construction, lead time, politics, decentralization

I. INTRODUCTION

It is a stylized fact that the capital costs of nuclear power plants (NPPs) have historically trended upwards in Western developed nations. Some scholars have characterized this as "negative learning-by-doing" [1, 2]. This trend is often contrasted sharply with the steady downward trajectory of the cost of other electric generation technologies ("positive" learning-by-doing), particularly photovoltaic solar panels, wind turbines, and gas combustion turbines [3]. Budget overruns and schedule slippage in the construction of the AP1000 in the United States and the EPR in Europe indicate that the nuclear industry's economic woes have yet to be properly addressed. The problematic economics of NPP construction are representative of "megaproject syndrome," [4] a theory which applies to massive infrastructure projects broadly, including airports, urban public transit, high-speed rail, hydroelectric dams, and sports venues.

Academics and industry observers have offered numerous explanations for the root causes of the problem for the nuclear industry: construction project mismanagement [5], evolution in the political environment and regulatory regime [6], lack of standardization in design [7], reliance on immature or incomplete designs before beginning construction [8], diseconomies of scale [9], and added complexities in design arising from innovation in nuclear safety [10]. However, outside the West, historic trajectories and recent results in NPP construction suggest that an upward cost trend is not inevitable and lower costs are possible [11], although this interpretation and the credibility of the underlying data are disputed [12, 13]. The present work wades into this fierce debate with two primary contributions: (1) novel, rich data on the design specifications of NPPs, and (2) a quantitative analysis that connects the study of the nuclear industry to the literature of institutional political economy.

Previous studies of this industry have been haunted by the specter of omitted variable bias: simple cross-country and time-trend analyses of NPP construction outcomes are not necessarily valid for causal inference given that the technical characteristics of nuclear power plants vary across countries and over time [14]. The present work is the first of its kind (to the author's knowledge) to incorporate detailed data that "look inside" a nuclear reactor. These include such variables as the operating temperature and pressure of the primary coolant, the number of primary coolant loops, the size of the reactor pressure vessel, the choice of cooling technology, the design of the containment structure. Previous work has been largely limited to power output in megawatts and categorical classifications of the make and model of reactor. Unfortunately, due to the terms under which I accessed this data from IAEA, much of the underlying data cannot be publicly made available for replication. Nevertheless, nearly all of the analyses I present herein can still be replicated with the data I have provided in the online data appendix.

In seeking to explain the high degree of cross-national variation, I observe the long and storied history local opposition as a factor in the siting, regulation, construction, and cancellation of NPPs. I argue that the political economy of nuclear power is characterized by locally concentrated risks and diffuse national (and global) benefits, in an inversion of the standard problem formalized by Olson [15]. Hence, NPPs are expected to face greater regulatory hurdles and political constraints in countries whose subnational governments have greater autonomy and institutional capacity. This generates a suite of hypotheses regarding how the degree of federalism or regional autonomy ("decentralization," for brevity) influences the design characteristics of nuclear reactors, the economics of their construction, and the industry's ability to improve upon past performance through learning.

To perform the analysis, I combine the technical data on reactors with economic and political data regarding the nation in which the NPP was constructed, including democracy, regime change, decentralization, national level of economic development, and utility ownership (public or private). In the present work, I take lead time (LT) as the primary outcome of interest, due to data availability and quality issues associated with overnight capital cost (OCC) data.

There are three key findings of the paper. First, I find no significant association between a nation's political conditions and the expected lead time of the NPPs, conditional on their design specifications, it builds. Instead, I show that otherwise technically identical NPPs tend to take longer to build in more highly decentralized nations. The estimated effects imply that one standard-deviation increase in a nation's political decentralization is associated with roughly a 9% increase in lead time, which amounts to about 8 months longer for a typical light-water reactor (LWR) on the order of 1GW in size. However, more data collection and cleaning on safety-related design specifications is needed to strengthen the credibility of this finding.

My second key finding relates to the theory of "megaproject syndrome" [16]. As previous research has shown, larger NPPs take longer to build and I replicate that result here. I extend this finding in two ways: I generate a more comprehensive measure of scale and project complexity, namely an NPP's expected lead time conditional on its size and design specifications (absent any political or economic variables). Then, I show that expected lead time does not correlate with observed lead times in a one-to-one relationship in all countries. In particular, I show that East Asian nations have historically completed construction of their NPPs much faster than would otherwise have been expected on account of the "megaproject-iness" of their NPPs. More generally, I show that political decentralization makes harsher the penalty to lead time that arises from scale and complexity. The size of this effect implies that a typical gigawatt-scale LWR which faces an expected lead time in of 42 months in an average country would instead be expected to take around 66 months to build in country that is otherwise identical except in possessing a decentralized political system comparable to that of the United States, Canada, Germany, or Switzerland.

My final key finding pertains to long-running debates over the apparent absence of learning-by-doing in the construction economics of NPPs. I argue that cumulative experience has been mismeasured in the nuclear sector due to faulty application of methods and concepts that are more appropriate for modular electricity generating technologies. I estimate empirical learning curves that describe the relationship between cumulative experience and LT. I find that learning rates vary according the level of decentralization in a country, ranging from 1.1% in the most centralized countries to -5.5% in the most decentralized countries. For a family of reactors with cumulative experience equivalent to that embedded in present-day Westinghouse PWR technolgy (i.e. 8 cumulative doublings of total deployment), a -5.5% learning rate translates into total increase in LT on the order of 50% relative to the first project. However, because cumulative experience and the size of a reactor are closely correlated, this finding of negative learning is not distinguishable from the finding regarding megaproject syndrome, at least not with the methods used in the present work paper.

The outline of the paper is as follows. Section II reviews the literature and elaborates the theory that motivates the empirical analysis. Section III summarizes the dataset assembled for this paper. Section IV formally lays out the econometric specifications. Section V presents the results. Section VI discusses the results and proposes directions for future research. The data sources, cleaning, coding procedures, and restrictions on the availability of the data are detailed in Appendix A. Appendix B addresses several methodological issues and assumptions.

II. BACKGROUND, THEORY, AND PRIOR WORK

II.A. Measurement of Capital Cost in the Electricity Sector

The two most widely studied outcomes in the literature on NPP construction are overnight capital cost (OCC) and lead time (LT).

OCC consists of all outlays on materials, manufactured components, construction equipment, construction labor, engineering services, land, and permitting costs. These are what economists call accounting costs. The designation “overnight" refers to the hypothetical case of a power plant constructed from start to finish over the course of a single night. Effectively no interest would accumulate during construction. While not a complete measure of capital cost, OCC enables comparisons of the capital costs of different NPPs independently of financing parameters, which can vary due to macroeconomic conditions, government policies to subsidize the cost of capital, and other factors outside the control of the firm building the plant.

[Figures 1 and 2 about here]

LT denotes the length of time between initiation of major construction activities and the start of commercial operation. By convention in the nuclear industry, this is typically measured from the first day of pouring of concrete for the foundation of the plant [17]. The start of commercial operation is usually “declared” after several weeks to months of test operations have been completed and the plant begins operating full time. Because NPPs require a considerably longer amount of time to construct than competing technologies in the electricity sector, financing costs account for a comparatively greater proportion of capital costs for NPPs, around 17% under ideal conditions [18, 19] and even higher when delays stretch out construction schedules. The opportunity cost of capital during the construction period is commonly called “allowance for funds used during construction” (AFUDC) in the electric utility sector.

II.B. Prior Quantitative Studies of OCC and LT

In this section, I will primarily review studies that estimate the effect of underlying casual determinants of OCC and LT for NPPs. But first I will briefly mention the prior works that collected and presented the necessary data on which subsequent analyses rely. These works have successively expanded data availability from the United States [6, 20], to France [1, 21], to several other OECD nations [11], and finally 82%[1] of the global population of reactors [22]. However, unlike the studies below and the present work, most of the foregoing works (with the exception of [21]) do not analyze the underlying causal determinants of LT or OCC in a quantitative or systematic way.

Berthélemy and Escobar Rangel [10] estimate a system of equations for OCC and LT in the United States and France. They find that the French policy of standardization helped reduce cost escalation and schedule slippage relative to the U.S. experience. Their estimated learning effects are conditional on experience from previous NPP construction being accumulated by the same architect-engineer (AE) firm with the same reactor model. Notably, the U.S. market for nuclear reactor design was contested by four major suppliers of nuclear reactors whose designs were routinely adjusted by approximately twenty different AE firms to meet the requirements of different utilities. In contrast, the French market was monopolized by Framatome as reactor supplier and monopsonized by the state-owned national utility, EDF, which performed in-house architect-engineering for its plants.

In addition, Berthélemy and Escobar Rangel estimate a model of LT alone on a larger sample, adding observations from Canada, the United Kingdom, Japan, and South Korea. This analysis lends further support for the hypothesis that standardization of reactor design helps to reduce lead time.

LT of the global population of NPPs was investigated by Csereklyei et al. [7] using duration analysis.[2] The authors find several economic conditions influence NPP construction: higher levels of GDP per capita, higher expectations of future economic growth, and higher oil prices are associated with shorter lead times. Furthermore, they find partial evidence for the benefits of standardization. They show some—but not all—reactors of certain standardized designs tended to be built faster compared to those of non-standardized design.

Regarding political factors, Csereklyei et al. find both autocracy and democracy are associated with faster construction, where anocracy (Polity IV[3] score between -5 and +5) is the reference

---

[1] Portugal-Pereira et al. [22] limit their analysis to light water reactors, but the data appendix provides OCC for 521 reactors out of 636 which have been completed as of September 25, 2020.

[2] Duration analysis is also known as "survival analysis," so-called because it is classically used to estimate patient survival after a medical treatment. However, the method extends naturally to modeling the length of time between any two events.

[3] See Appendix A.II for discussion on the Polity IV democracy-autocracy index.

category. But the standard errors on the effects are very large; they find a statistically significant effect of democracy in only one econometric specification. They find no statistically significant effect of the accidents at Three Mile Island (TMI) or Chernobyl on lead time, which contrasts sharply with the conventional wisdom among industry observers, prior academic findings [10], and the results I find in Table VII in Section V.B.

In a series of three closely related papers [2, 23, 24], Sovacool et al. analyze a sample of 401 projects in the electricity sector, consisting of several different types of power plants (fossil, nuclear, solar PV, solar thermal, wind, biomass) and high voltage transmission lines. They present data on budget overruns and schedule slippage (i.e. increased in OCC and lead time relative to original estimates). Comparing all the types of projects studied, they find that (1) NPPs most frequently exhibit budget overruns and (2) NPP budget overruns are, on average, the largest as a percentage of initial budget relative to all other technologies considered. Another noteworthy finding is that budget overrun and schedule slippage are positively correlated with each other for nuclear power plants.[4] This is consistent with the findings of Ref. Portugal-Pereira et al. [22], who report a correlation of r=0.48 between OCC and LT. United Engineers and Constructors [25] (an American architect-engineer firm involved in several NPP projects) attribute the relationship between time and cost to the effect of delays on labor productivity. For example, failed inspections and design changes are said to have a "triple penalty"—the cost of the initial work, the cost of removing the initial work, and the cost of performing the work again. Such work comes also comes at the cost of a longer lead time.

For the present work, I have selected LT as the sole outcome of interest for several reasons. First, the data are available for the global population, which bolsters statistical power. Second, LT is a more transparent and consistently recorded metric, whereas OCC data are subject to disputes regarding accounting practices, inflation adjustment, currency conversion, and trustworthiness of data sources. Third, LT is an economically important outcome *per se*, as it plays an essential role in the accumulation of financing costs during construction and schedule slippage tends to correlate with budget overruns. Lastly, modeling the endogenous interactions between OCC and LT is beyond the scope of the present work. Future research could extend the present work by modeling the simultaneous determination of OCC and LT as in Berthélemy and Escobar Rangel

---

[4] The authors report an R^2 of 0.316 in regression of schedule slippage on budget overrun, using a polynomial fit. The estimated fit is nearly linear, so the implied coefficient of correlation is approximately 0.56.

[10] while using the OCC data compiled by Portugal-Pereira et al. [22].

II.C. Learning-By-Doing

Learning-by-doing is a theory of endogenous technological change that ascribes cost reductions and quality improvements to the accumulation of practical experience with a production process [26]. The conventional model of learning-by-doing posits the following relationship between some outcome Y_t (typically, cost per unit) and cumulative experience, Exp_t, based on the work of Wright [27]:

$$ln(Y_t) = \alpha + \beta ln(Exp_t) + \epsilon \tag{1}$$

Assuming lower values of the outcome are more desirable, the production process is said to exhibit learning-by-doing when $\beta < 0$. In practice, as a technology matures, the level of the outcome over time ceases to be characterized by Equation 1 and reaches some relatively stable level. This level would be determined exogenously by physical limits to the production process and the price of inputs.

A common method for contextualizing the magnitude of β is the progress ratio (PR) or learning rate (LR):

$$1 - 2^{\beta} = 1 - PR = LR \tag{2}$$

PR is interpreted as the relative level of the cost (or other outcome) after a doubling of cumulative production as compared with the prior level; LR is the percentage reduction in cost (or other outcome) arising from a doubling of cumulative production. For example, $\beta = -.32$ generates $PR = 80\%$ (a cost equal to 80% of the prior level) and $LR = 20\%$ (a 20% reduction in cost).

Several improvements to the operating performance of nuclear power plants have been documented, such as increased reliability [28, 29], increased power output [29, 30], reduced occupational exposures to radiation [31], and reduced rates of initiating events (precursors of more serious safety problems) [32]. However, the empirical evidence regarding learning in NPP construction paints a more dismal picture. Rubin et al. [3] survey the literature on learning-by-doing in the capital costs of energy technologies, reporting mean one-factor[5] learning rates of 15% for natural gas com-

---

[5] The foregoing discussion has been solely of one-factor (cumulative experience) learning. Two-factor learning encompasses cumulative experience and the stock of knowledge. See Wiesenthal et al. [33] for further discussion.

bustion turbines, 12% for wind turbines, 23% for solar photovoltaic (PV), and 11% for biomass generation, *inter alia*. Their review of learning rates for nuclear power captures only four studies, which report values ranging between -38% [1] and 5.8% [34]. Subsequent to the public release of more authoritative data on the costs of France's nuclear reactor fleet, Rangel and Lévêque [21] argued that the cost estimates underlying the calculations of Grubler [1] were too high for later reactors. The findings of Berthélemy and Escobar Rangel [10] correspond to a learning rate of 10%,[6] conditional on the same design of plant being built by the same architect-engineer.

One hypothesis for the poor rate of learning in NPP construction is the high degree of on-site construction work as a share of the total cost. Estimates from United Engineers and Constructors [25] suggest that equipment manufactured off-site accounts for approximately 21% of the base cost[7] of a typical American pressurized water reactor built in the 1980s. Factory fabrication is theorized to better facilitate learning-by-doing [35], for reasons such as assembly line production methods, a stable workforce, and consistent and well-controlled workplace conditions. Lessons learned at one construction site may not disseminate as readily to another site.

A strong contrast can be drawn between nuclear fission and solar PV in this respect. The price of PV modules constituted 74% of the total cost of rooftop solar panel installations in Germany in 2007; following dramatic declines in global module prices, that share fell to 39% as of 2019 [36]. This decline is consistent with evidence for faster learning in PV module manufacturing than in PV module installation. Elshurafa et al. [37] estimate a learning rate of 11% for balance-of-system costs of solar PV installations, whereas the median learning rate for PV modules among the studies included in Rubin et al. [3] is 20%.[8] Furthermore, the high initial share of cost associated with the module provided a greater scope for manufacturing-based learning effects to reduce the overall capital cost of solar PV.

Many commentators emphasize the role of standardization in fostering beneficial learning effects in the nuclear industry [10, 11, 21, 38]. However, technologies such as solar panels, wind turbines, and gas combustion turbines appear to have achieved considerable learning despite a much larger number of firms engaged in each industry, with each firm offering competing designs, relying on proprietary innovations, and regularly introducing new product lines. Why is it that

---

[6] $1 - 2^{-.152} = 10\%$

[7] Author's own calculations from Table 5-3.

[8] Author's own calculations from Table A3 of [3].

cumulative industry experience is a meaningful predictor of cost reductions for these technologies but not for nuclear power?

To illustrate this, consider the example of General Electric (GE), a large multinational firm engaged in a variety of industries, including several different energy technologies. GE currently advertises 21 different models of gas combustion turbine on its website [39], many of which come in two different versions depending whether the customer's grid runs at 50 Hz or 60 Hz. This high diversity of product offerings—and the development costs that each product entails—is sustained by a large volume of orders. GE boasts that over 1,100 of its F-class turbines have been installed at power plants to date [39], the first of which entered commercial operation in 1990 [40]. GE claims sales of over 3,000 units of its smaller B and E class turbines. Such a high volume of sales can sustain serial manufacture of several different, standardized models.

Now consider GE's involvement in the nuclear industry. GE was the first commercialize boiling water reactor (BWR) technology, beginning with Dresden Unit 1 in 1960. To date, a mere 99 commercial-scale BWRs have been built by GE and firms to which it licensed its technology. These 99 reactors consist of several different product lines and most of these exhibit a staggering degree of internal diversity [41]. BWR-1 is a designation retroactively applied to a hodgepodge of early experimental designs, which is perhaps to be expected in the early stages of technological development. The first BWR-2 (Oyster Creek) was obsolete before it had even entered commercial operation (Dec. 1, 1969) as GE had returned to the drawing board so quickly that the first BWR-3 (Dresden Unit 2) had begun construction several years earlier (Jan. 10, 1966). BWR-4s and BWR-5s have been mixed and matched with the Mark I and Mark II containment designs.[9] The BWR-6 started to exhibit more standardization; it was exclusively paired with Mark III containment and GE applied to the US Nuclear Regulatory Commission for approval of a "Standard Safety Analysis Report." Yet the BWR-6 was offered in three different sizes of reactor pressure vessel, each requiring its own safety analysis. The first truly standardized BWR was the ABWR, of which four have been completed to date. While the scale of GE BWR installed base is impressive in terms of megawatts (roughly 82.5 GW), the scope for learning through repetition of a standardized design has been historically quite narrow.

Of course, learning-by-doing is not limited to improvements in the ability of workers and

---

[9] Seven BWR-5s were built with Mark I containment in Japan by Toshiba and Hitachi, licensees of GE technology.

firms to perform an production process more efficiently. It also encompasses improvements in the design of the product. For example, a reduction in the number of primary coolant loops from 5 to 2 was a major breakthrough in the design of the BWR-3 and a reason for the quick discontinuation of the BWR-2. David and Rothwell [42] consider the question of how firms balance between the competing considerations of standardization and experimentation through diversity. On one extreme, consider repeated construction of identical plants, which permits learning only to occur in the efficiency of the manufacturing and construction process. On the other extreme, imagine iterated construction of one-of-a-kind plants. Such diversity provides fertile ground for experimentation and allows for the possibility of improvements to the design of future plants. However, it comes at the cost of workers and managers constantly readjusting to a new production process, as well as fixed development costs for each new design. Of course, between these two extremes exists a continuum of possibilities. The appropriate balance between experimentation and standardization is a problem of dynamic optimization under considerable uncertainty.

II.D. Megaproject Syndrome

An alternative hypothesis regarding learning in NPP design and construction is the view learning did indeed occur, but the cost-reducing and time-saving effects of learning were swamped by countervailing factors. Prime suspects for countervailing factors include upward ratcheting of safety requirements [43], regulatory delays in the granting of operating licenses [19], and diseconomies of scale [9, 38]. One theoretical explanation for diseconomies of scale concerns the dispersal of decay heat after a reactor is shutdown. "...[C]ore power (and decay power) is proportional to the volume of the core, which varies as the cube of the effective core radius. On the other hand, heat removal from the vessel is proportional to the vessel surface area, which varies roughly as the square of the core radius."[38] Thus, as reactors grew in size, ever more powerful and elaborate systems were needed to ensure control of decay heat under emergency conditions.

However, if diseconomies of scale are present in nuclear power plants beyond a certain size, then it is puzzling why some firms in the industry continue to pursue even larger designs, such as the EPR (1,650 MW) and the APR-1400 (1,340 MW). Surely identifying optimal scale is part of the learning process. The promotion of SMRs and the proliferation of venture-capital-backed firms pursuing SMR development implies a lack of consensus within the industry regarding what lessons should be learned from initial scale-up of NPPs.

A large academic literature on so-called "megaproject syndrome" theorizes that persistent economic the construction of large-scale infrastructure is not merely a failure of technical optimization [4, 44, 45, 46]. Nuclear power plants are but one category of megaprojects; examples of others include dams, airports, bridges, tunnels, harbors, public transit, and high-speed rail. Uniting characteristics of megaprojects include: a budget above $1 billion (although some authors argue for lower thresholds in certain sectors or in the context of less developed nations); customization as necessitated by unique geographic conditions or customer requirements; extensive involvement of the public sector in matters such as planning, permitting, and financing; complex management challenges arising from a large number of subcontractors.

Several theories have been considered in the literature regarding the high propensity of megaprojects to run over budget, fall behind schedule, be abandoned prior to completion, and fail to deliver the level of benefits promised once in operation. The classical view is that the incentive structure faced by politicians and project managers produce optimistically biased and/or strategically underestimated estimates of cost and schedule [16]. Alternative views emphasize, *inter alia*, scope change [47], corruption [48], cross-purposes and infighting among project partners [49], and relations with external stakeholders (i.e. parties other than the project owner and the firms delivering the project) [50]. I take the view that all of these theories are in no way mutually exclusive; in some cases, they could be mutually reinforcing. However, in this paper, I focus on the role of external stakeholders—the local community, civil society organizations dedicated to the environment or advocacy for utility ratepayers, and enterprising politicians—in contributing to megaproject syndrome. I theorize that a higher degree of political decentralization enables external stakeholders to more substantively impact the design, permitting, and construction of megaprojects such as nuclear power plants.

II.E. Decentralization

Decentralization has been in vogue as a development strategy promoted by major international institutions (e.g. the World Bank and International Monetary Fund) since the closing decades of the 20th century and the recommendation has been increasingly accepted by a variety of countries [51, 52, 53]. The advice is motivated by a large and well-established literature that spans political economy, economic history, and development. Purported benefits of decentralization include greater public sector efficiency [54], greater accountability [55], lower corruption [56], opportunities for yardstick competition [57], and self-enforcing government commitment to markets [58].

However, there may be limited applicability of the lessons from the broader literature on decentralization and development to the case of nuclear power. Historically, national governments have assumed sole authority for the regulation of safety at NPPs, with the notable exception of West Germany (and reunited Germany post-1990), where authority is shared between the *länder* and the federal government. National control of nuclear safety regulation limits the scope of any potential subnational competition for efficient regulation of the industry to policy areas such as land use, environmental permitting, and rate-setting for regulated electric utilities. These are important aspects of the regulatory environment faced by firms in the nuclear industry, and they have a long history as the setting for political conflict over nuclear power [59], as will be discussed further in Section II.F.

The consequences of what might be considered "inefficient regulation"—such as delaying or cancelling the construction of nuclear power plants and discouraging investment in the nuclear supply chain—are often intentional. The literature on decentralization primarily studies outcomes that are valence issues for voters—that is, issues on which all voters agree on the desired outcome, even if they may disagree on the optimal policy to achieve that outcome. Examples of valence issues include economic growth (faster is better), crime rates (lower is better), and corruption (lower is better). How does decentralization operate when the issue in question is a controversial technology over which opinions differ?

II.F. Local and Regional Opposition to Nuclear Power Plant Siting

The politics of nuclear power has historically featured opposition by citizens, civil society, and politicians who are geographically near the site of proposed and existing NPPs. This has been documented in the United States [59, 60, 61], France [62], West Germany [63], the United Kingdom [64], several separatist regions in Western Europe [65], Japan [62], and even the Soviet Union in its final years [66]. Such opposition is often characterized by the acronym NIMBY ("not in my backyard")[62, 64]. Some scholars view the term as inherently pejorative, conveying a normative disapproval of opponents' position and motivations [67]. To avoid the appearance of passing an unnecessary normative judgement within the context of a positive analysis, hereafter I characterize the phenomenon as local and regional opposition to NPP siting, or "local opposition" for brevity.

The success of local opposition to NPPs has varied widely across nations, regions, and communities. A natural explanation is to attribute siting outcomes to the magnitude and persistence of mobilization campaigns. In *Site Fights*, Aldrich [62] provides a comparative history of local opposition to NPP siting in Japan and France. Meaningful contestation of pro-nuclear policy in the national halls of power was almost entirely absent in both countries in the late twentieth century. Furthermore, both Japan and France are unitary nations, meaning all sovereignty is vested in the national government. Thus, the ability of local and regional governments to conduct policy at cross-purposes with the central government is necessarily circumscribed.

However, France and Japan contrast sharply with respect to actions taken by their central governments to ameliorate or overcome local opposition. Initiatives by the Japanese central government tended toward "soft social control": propaganda, public meetings, offering tours of other nuclear power plants, and most especially generous transfer payments *à la* Coase to municipalities, fishermen, and farmers. France, by contrast, engaged in the methods of "hard social control," such as police presence (and police violence), expropriation of land, surveillance, secrecy, restrictions on public participation, and simply ignoring local opinion. Aldrich argues that the difference in approaches resulted from the persistence of opposition in Japan and the withering away of opposition in France. In the face of persistent opposition, the state is obliged to "win hearts and minds." Conversely, if opposition demobilizes after a proverbial "whiff of grapeshot," the state sees no need to take another approach. Comparing the results of the French and Japanese nuclear programs, Aldrich writes:

> *Analysts point out that without only a few exceptions, "the government [of France] implemented its initial plans" for siting reactors (Rucht 1994, 153), an accomlishment far surpassing Japan's record, where close to half the sitings failed.*

While Japanese utilities regularly withdrew proposals in response to local opposition, it seems likely that they benefited considerably from only moving forward with construction in communities that had agreed to host NPPs. Once regulatory approval is granted and construction begins, the lead time for constructing and commissioning an NPP in Japan has historically been extraordinarily fast and stable, averaging 4.7 years[10] and showing modest declines from the 1970s to the 1990s. By comparison, the global average lead time is 7.3 years. Construction in France was once faster than the global average, as well, averaging 6.2 years for plants starting construction in the 1970s or earlier, but that figure has has consistently trended upwards, averaging 9.0 years for the plants built in the 1980s and later.

Circumstances in Japan and France contrast sharply with those in United States, where local opposition has historically been neither placated nor denied political and legal avenues by which to obstruct NPP construction. Cohen et al. [68] argue that a multiplicity of veto points in the constitutional design of the United States laid the groundwork for vigorous contestation of nuclear policy, including at the state and local level. Emphasizing the federal nature of the United States, Joppke [59] points to three specific issues for which local opposition played an important role in delaying and cancelling NPP construction:

> *The three predominant issues of the U.S. nuclear power controversy in the 1980s—emergency planning, utility rate regulation, and waste disposal—are all similar in this regard. In each case, local citizen groups formed effective alliances with local and state authorities in opposition to particular nuclear facilities or federal regulatory agencies.*

Critical Masses: Opposition to Nuclear Power in California, 1958-1978, by Wellock [60], is instructive of the causal mechanisms by which political decentralization would tend toward lengthening NPP lead times globally. For example, Diablo Canyon Power Plant in California was the target of public protests throughout its construction period, drawing record-breaking crowds, celebrities, and governor Jerry Brown. Seismic safety was among activists' leading concerns about the plant. State bureaucracies such as the Natural Resources Agency, the State Lands Commission, the Public Utilities Commission offered ample opportunities for local opposition groups to intervene in the process, demand transparency from the utility, and force it to adjust its behavior. While construction of Diablo Canyon had begun in 1968 and was effectively complete in 1973, it was not permitted to enter commercial operation until 1985 after major seismic retrofits. While formally licensing decisions were in the hands of the federal bureaucracy, Wellock presents a strong case for the role of state government and local activists in pushing for stricter regulatory scrutiny.

---

[10] Author's own calculations from IAEA PRIS. This average is for plants which have been completed as of the time of writing. Thus, two reactors that remain under construction are excluded.

A principal theme of *Critical Masses* is the emergence of a post-materialist environmentalist ethos. This ethos places little weight on economic concerns, distrusts technocrats and technocratic institutions, and emphasizes values such as local control, preserving the aesthetic character of natural vistas, and opposition to war. Berndt and Aldrich [61] report empirical evidence from the United States that proposed and under construction NPPs were more likely to be abandoned in counties with higher incomes, which they consider to be a proxy measure of post-materialist values. On the other hand, Berndt and Aldrich find no relationship between local political affiliation and siting outcomes. They posit that ideological stances on environmental issues had not yet been mapped onto polarized partisan identities as they are in the present day.

Several authors have commented on the importance of a coherent, stable, long-term policy commitment to the nuclear industry in enabling its success. Delmas and Heiman [69] argue that fragmentation of power prevented the United States from making such a commitment. In case studies of China, India, South Korea, and Japan, Sovacool and Valentine [70, 71] conclude that "centralization of national energy policymaking and planning" is one of six key factors for successful NPP deployments. They note, for example, that "in South Korea, the Office of Atomic Energy was placed directly under the President and the nuclear program was structured as a monopoly under the Korea Electric Power Corporation." However, even South Korea—arguably the world leader in centralization, standardization, and successful learning-by-doing in the nuclear industry [11]—offers a lesson in how decentralization can impede timely NPP construction:

> *Yonggwang*[11] *was one of the first of the state-owned utility (Korea Electric Power Co — KEPCO) projects to attract serious local opposition. Political reform in South Korea has devolved some power from the centre. Local politicians in Yonggwang used their new strength to slow down construction.*
>
> *Hanjung (Korea Heavy Industries and Construction) was due to begin construction in December 1995, but a delay was brought on by the cancellation of construction permits for the site by Yonggwang County, South Cholla Province.*[72]

---

[11] Yonggwang NPP was renamed Hanbit NPP in 2013.

II.G. The Logic of Local Democratic Control

In this section, I draw on the framework of Mançur Olson's seminal work, *The Logic of Collective Action* [15], to argue that the spatial distribution of costs and benefits from nuclear power plants tends to generate a pattern of support by national governments and opposition by local and regional governments. The reasoning follows along the same lines as those in the introductory chapter of *Site Fights* [62].

The standard problem considered by Olson posits some policy provides concentrated benefits to a small group and diffuse costs to the rest of society. Lobbying the government to advocate for or against the policy requires overcoming a collective action problem, as no one individual can meaningfully influence the outcome. Olson argues that this situation inherently favors small groups for two reasons. First, the costs of overcoming collective action problems (such building sufficient solidarity to overcome free-riding incentives and coordinating on a common strategy) are increasing in group size. Second, the benefits of a policy change can be quite large on a per-person basis for the sorts of small groups and policies typically considered.

To analyze the political economy of nuclear power plant construction, I modify Olson's problem in three ways. First, I give a spatial dimension to group identity and interest: proximity to a proposed nuclear power plant. Those who live within the range of a hypothetical evacuation or exclusion zone in the event of a catastrophic nuclear accident are the small group; those who live further away and yet would still benefit from the plant in some way are the rest of society.

Next, I invert the distribution of costs and benefits. The small group faces a geographically concentrated risk while the rest of society stands to gain geographically diffuse benefits. Of course, there is also a geographically concentrated benefit in the form of increased local economic activity. However, it is not unheard of for residents to regard this benefit as a cost. Local opponents of a proposed nuclear power plant near Bodega Bay, California argued that a large industrial facility would ruin the rustic charm of their small fishing community by attracting further development [60].

The primary diffuse benefit of interest is the electricity produced by the plant, which can be transmitted by the electricity grid to households and firms hundreds of miles away. The electricity may not be particularly valuable if substitute sources of electricity can be had at little, zero, or negative additional cost. However, other diffuse benefits include clean air and water,[12] lessening of national dependence on expensive energy imports,[13] complementarities with national nuclear weapons development, [14] and interregional technological spillovers arising from learning-by-doing.

In a final modification of Olson's original framework, I observe that democratic subnational government is a ready-made solution to the collective action problem faced by local residents who oppose a nearby nuclear power plant. Elected politicians are strongly incentivized to care about the interests of constituents in their jurisdiction and may take on the cause of opposing NPP construction as an electoral strategy. Even when the issue does not immediately arouse the attention of subnational politicians or those politicians favor the plant, the subnational government offers a more convenient forum with lower transaction costs in which local opponents of a nearby NPP can mobilize and seek to effectuate policy. A subnational government with sufficient autonomy and institutional capacity can directly intervene to regulate NPP construction on issues such as land use, environmental protection, or economic regulation of utilities without ever needing to lobby or influence the national government.

Of course, the reasoning here can be applied to a variety of political economy problems of a spatial nature, such as residential zoning, routing of high-speed rail lines, and the provision of services to the mentally ill and homeless. In the case of nuclear power, I propose it may explain the patterns we see in the data on NPP lead times.

III. DATA

I assembled a database of all commercial nuclear power reactors which have ever initiated construction, as of December 31st, 2019. The observations are identified by the Power Reactor Information System (PRIS) of the International Atomic Energy Agency (IAEA). While certain basic information about each NPP is available on the IAEA's public website and through their various publications, I was granted temporary access to a private version of the PRIS database restricted to authorized users. The dataset I have assembled offers considerably more detail and

---

[12] Assuming the substitute sources of electricity are polluting. Historically, this has been the case [73].

[13] Even for nations which depend on uranium imports, importing uranium is much cheaper per unit of final electricity generated than fossil fuels. Provided the nation is a signatory to the Non-Proliferation Treaty, availability of supply is a non-issue.

[14] Of course, nuclear weapons programs generate negative externalities globally but plutonium recovered from spent nuclear fuel is often considered a benefit by national policymakers who desire nuclear weapons.

comprehensiveness than any other prior work on this topic, to my knowledge. Past studies are typically limited to variables such as size of the reactor in megawatts, general type of reactor (PWR, BWR, etc.), the identity of the NSSS design firm, and a coarse coding of reactor models [e.g., 7]. The most fine-grained coding of reactor models can be found in the data appendix to Portugal-Pereira et al. [22]. However, it suffers from the inconsistencies present in the raw IAEA PRIS data. For example, American BWR are coded as a concatenation of the design of NSSS (BWR-1, BWR-2, etc.) and the design of the containment structure (Mark I, Mark II, Mark III). BWRs in other countries are purely coded by their design of NSSS. Similar inconsistencies are present in PWRs.

Unfortunately, the terms and conditions of my access to PRIS prohibit me from sharing any of its data that is not otherwise publicly available. This primarily means I cannot share any design specification data that is not otherwise publicly available. In any case, my coding of reactor models, and several other independently collected, cleaned, and calculated variables are available in the online Data Appendix.

III.A. Description of Reactor-Level Variables

The final dataset includes the following variables for each reactor:

Site Name and Unit Number: A nuclear power plant consists of one or more "units" which can generate electricity independently from one another. Each plant has a name and each unit has a number or letter to distinguish it from others at that site. Units at the same site typically begin construction and enter operation at distinct times from one another. Units that began construction around the same time typically are identical units; when there is large difference in age, they typically differ in their design. On average, at sites with more than two more units, the average unit shares a site with 2 other units of a different model of nuclear steam supply system (NSSS).

Therefore, they are the unit of analysis. For brevity and to avoid confusion with other uses of the word "unit," I refer instead to "reactor" as a metonym for "nuclear generating unit," which consists not only of a reactor but a great deal of other equipment and infrastructure, such as containment structures, cooling towers, steam turbines, and switchyards connecting to the electricity grid.

Country: Construction of the first observation in the dataset commenced in 1951, and several major changes in international borders have occurred since that time. For the purposes of the analysis, a reactor's "country" is whichever country had territorial sovereignty over its site as of the year construction begins. For the handling of changes in national borders, see Appendix **??**.

Lead Time: Lead time is computed as the amount of time between the date on which construction began—listed in PRIS as the first day on which pouring of safety-related concrete for the foundation—and the date of commercial operation.

Capacity in Megawatts: I define capacity as the net electric output in megawatts according to the original design, ignoring any subsequent uprates or downrates of capacity.

NSSS Manufacturer: PRIS provides the name of manufacturer of the NSSS, the system which comprises all the hardware involved in the process of generating steam from nuclear fission.

Utility Type: I generate a categorical variable indicating whether a utility is majority investor-owned or state-owned.

Reactor Type: PRIS uses the term "type" to encapsulate broad similarities in the principles of a reactor's design. The most common types are pressurized water reactors (PWR), boiling water reactors (BWR), pressurized heavy water reactors (PHWR), gas-cooled reactors (GCR), and light water graphite reactors (LWGR). All other types were aggregated into a category called "other" due to a sparsity of observations.

Reactor Family: I use the term "family" to classify reactors that have a shared evolutionary heritage. This classification is narrower than reactor type in that encompasses only reactors by a single firm or a small set of firms which have a history of licensing intellectual property and collaborating with one another. The classification scheme is detailed in Appendix A.

Reactor Model: I use the term the name of the model assigned by the manufacturer, where applicable. Examples of model names assigned by the manufacturer include AP-1000, CP1, P4, OPR-1000, CNP-300, VVER-213, and ABWR. For standardized reactor designs, this identification comes as close as realistically possible to identifying "identical" reactors. However, for non-standardized designs, PRIS provides an abbreviated, generalized description of the reactor's design in place of a model name. For example, "WH 4LP (DRYAMB)" indicates that the reactor is a Westinghouse design with four primary coolant loops and the containment structure operates at ambient atmospheric pressure.

Design Characteristics:[15] The design characteristics available are too numerous to list. A few examples include the number of primary coolant loops, reactor outlet and inlet temperature, percentage of fuel enrichment, and method of discharging waste heat. See Appendix **??** for a more thorough description of the data.

Standardization: I code every reactor as either standardized or non-standardized. The coding scheme is detailed in Appendix A.

III.B. Description of Country-Level Variables

The reactor-level data were merged with country-level data on economic and political conditions. Except where otherwise specified, a reactor was assigned the value of the country in which it was located as of the year it begin construction. See Appendix A for detailed definitions, data sources, and coding procedures.

GDP per capita: I draw from the Maddison Project Database [74] for its historical estimates of GDP per capita.

Democracy: I use the "Polyarchy" index of electoral democracy provided by the Varieties of Democracy (V-Dem) Project [75].

Decentralization: I use "Division of Power" index, also from V-Dem. This index measures whether local and regional governments exist, whether they have elected offices, and the extent to which elected local and regional governments can "operate without interference from unelected bodies at the local [and regional] level[s]."

Regime Change: I rely on data from Polity IV to identify the dates and magnitudes of changes of a country's constitutional structure or regime type. I assign a value of 1 to a reactor if it was under construction (or suspended) during an episode of major regime change, and zero otherwise.

[Table I about here]

---

[15] I use the phrases "design characteristics" and "design specifications" interchangeably throughout. I try to avoid using "design specifications" and "reactor model" in the same context as discussion of the econometric specification and model.

III.C. Summary Statistics

Table I lists the count of reactors in the dataset for each country, grouped by geopolitical region. Countries were assigned to regions based on a constellation of factors, primarily their alliances, form of government, and economic system during the Cold War. Geopolitics played a major role in the dissemination of civilian nuclear technology, especially in countries that imported foreign designs. Technology from the United States, France, and Canada dominated exports to Western-aligned nations while the satellite states of the Soviet Union almost exclusively adopted Soviet technology. The two blocs competed to export their technology to non-aligned countries.

The mean lead time in the dataset is 7.4 years, with a standard deviation of 3.33 years. There are clear geographic patterns to the data, as summarized in Figure 3. Notably, East Asian nations construct NPPs significantly more quickly and consistently, with a mean 5.5 years and a standard deviation of 1.4 years. The mean lead time in Western nations does not differ substantially from the global mean, which is perhaps unsurprising given that NPPs in Western nations account for 56% of the sample.

[Figure 3 about here]

Eastern Bloc nations exhibit nearly identical net lead times to their Western peers, however it is worth noting that they fare more poorly when compared on gross lead time: 7.7 years in the Western Bloc vs. 8.5 years in the Eastern Bloc. This is largely an artifact of the willingness of post-communist nations to resume construction on reactors suspended during regime transitions.

The nations of the Global South exhibit the slowest lead time. This may be a consequence of their comparatively lower level of economic development. As [7] write, "The wealth of a country indicates that (utilities in) countries possessing the necessary financial and structural resources will be completing their projects faster."

Summary statistics by type of reactor are presented in Table II. Light water graphite reactors (LWGRs), which were exclusively built in the Soviet Union, exhibit the quickest average lead time, as well as the lowest standard deviation. In a close second place are boiling water reactors, which are largely found in the Western Bloc and Japan. Pressurized water reactors (PWR) are exactly at the global average, which is unsurprising when they account for 56.3% of the global population. Pressurized heavy water reactors (PHWRs) perform relatively poorly, although this average is largely driven by outliers in Argentina and Romania (which suspended construction on theirs for many years due to economic and political conditions) and India, which consistently exhibits long lead times regardless of reactor type. Excluding these three countries (which account for roughly 40% of PHWR observations), the lead time of the remaining PHWRs is 6.7 years.

[Table II about here]

Table III reports the descriptive statistics for decentralization, specifically the V-Dem division of power index. The Pearson correlation coefficient between decentralization and lead time is a minuscule -0.008.

[Table III about here]

IV. ECONOMETRIC SPECIFICATIONS

Appendix B discusses an assortment of econometric issues that are common to many or all of the specifications which follow. Here, I summarize its conclusions briefly. In Section B.I, I argue that political institutions (democracy, decentralization, and regime change) are exogenous to nuclear power plant construction. In Section B.II, I account for a special type of measurement error that arises from serial construction. In Section B.III, I investigate possible selection bias arising from abandoned construction and conclude that it is negligible. In Section B.IV, I explain how I control for the effect of major nuclear accidents and political events on lead time using instrumental variables. In Section B.V, I define cumulative experience as the count of reactors of the same family as reactor i that began construction prior to reactor i. Table B.IV lists all abbreviations and symbols used in the equations for this section.

For lack of quantitative measures of cross-nationally comparable, site-specific local opposition, the hypotheses tested in this paper assume the presence of local opposition. Given the literature I reviewed in II.F documenting the presence of local opposition in both unitary and federalist nations, I argue that this is a reasonable, albeit imperfect, assumption. My analysis focuses on identifying the channels through which political decentralization enhances the efficacy of local opposition in slowing NPP construction and commissioning. While the credibility of the analysis *qua* causal inference is limited, the results can help guide future research by narrowing the range of likely explanations for the patterns in the data.

IV.A. Mechanism 1: Politically Constrained Design

While summary statistics show that NPP lead times tend to be longer in federalist nations than in unitary nations, we must ask whether they build comparable nuclear power plants. Federalist and unitary nations may systematically choose different designs of reactors that have differing technical, safety, and economic characteristics. Do lead times differ because of these differences in design, or is it because of factors beyond the design of the plant? To test this hypothesis, I conduct the analysis in two steps.

First, I investigate which design characteristics have meaningful impacts on lead time in a regression with country fixed effects. The country fixed effects are intended to generate credible estimates of the average treatment effect of design characteristics on lead time by leveraging within-country variation in design characteristics. The econometric specification is as follows:

$$ln(LT_i) = \sum_{s \in S} \theta_s Spec_{s,i} + \delta_r + \gamma M_i + \mu_c + \nu_t + \varepsilon_i \tag{3}$$

The year fixed are intended to control for a variety of time-related variables which might otherwise be spuriously correlated with the regressors. For example, gas-cooled, graphite-moderated reactors have fallen out of favor in the two countries that have historically built them in meaningful numbers, the United Kingdom and France. The estimated effect for this type of reactor—which both nations eventually judged to be technically and economically inferior to PWRs—could be biased downwards due to most of these reactors having been built prior to the emergence of mass movements against and stricter regulation of nuclear power. These time-related variables are not explicitly modeled because (1) they do not relate to the hypothesis being tested and (2) there is sufficient within-year dispersion in design characteristics to generate well powered estimates.

In the second step of the analysis, I generate the predicted values of a reactor's lead time conditional on its design characteristics, type, and M_i while omitting the country and year fixed effects. This represents a measure of a reactor's expected lead time in a hypothetical "average country" and "average year" conditional on its design characteristics.

I regress these expected values of lead time on country-level characteristics. Past research has found that nations with higher GDP per capita tend to complete their NPPs faster *ceteris paribus* [7]. In light of the strong correlation with political factors [76], I control for the natural log of GDP per capita in order to avoid any possible spurious correlation between level of economic development and form of government. I estimate the following equation by ordinary least squares:

$$ln(\widehat{LT_i}) = \beta_1 ln(GDPpc_{c,y}) + \beta_2 Dem_{c,y} + \beta_3 Dec_{c,y} + \varepsilon_i \tag{4}$$

This regression tests whether economic development and political institutions are associated with choices in the design of NPPs that entail longer or shorter lead times.

IV.B. Mechanism 2: Regulatory Delays

Second, I hypothesize that political decentralization generates conditions that cause construction to be temporarily halted or to proceed more slowly than would otherwise occur. This hypothesis proposes that, on average, otherwise identical reactors built in politically decentralized nations will tend to take longer to build than those in politically centralized nations, holding all else constant. The difficulty is in credibly identifying "otherwise identical reactors."

To begin, I include fixed effects for the model of reactor. I argue that this is a sufficient control for reactors which are of a standardized design (n=309), which share a common designation supplied by the manufacturer of the NSSS. Reactors of models that were only built once (n=48) are automatically dropped by the estimation procedure due to misleading causal inference that arises from singleton fixed effects [77]. Nine pairs of reactors built as twins at the same site are classified with a unique model name, although they are not classified as standardized because they were never replicated elsewhere. As a general rule, twin reactors at the same site are identical. This group presents no econometric concern but offers no cross-country variation to exploit.

The more challenging case is that of non-standardized "models" of reactors that have been built in more than one country (n=207). To account for the technically differing features of non-standardized models that may cause them to have shorter or longer lead times, I control for the predicted lead time (conditional on design characteristics) that was generated in Step 1 of the procedure outlined in Section IV.A. This approach maintains the parsimony of the econometric specification, as opposed to controlling for several dozen design characteristics. Furthermore, while the design characteristic data cannot be publicly released due to IAEA data sharing restrictions, no such restriction applies to the predicted values of lead time I generate from them. Thus, the data necessary to replicate this analysis can be made available.

I omit country fixed effects for two reasons. First, within-country, over-time variation in decentralization is exceedingly limited when considering how few countries have built nuclear power plants entirely before and entirely after major changes in their political institutions. Second, the cross-national variation in decentralization is of greater interest, as cross-national differences in nuclear power plant lead time is the outcome to be explained.

I do not include year fixed effects. Instead, I explicitly model the major events that are widely believed to have caused lengthy regulatory delays, per the instrumental variables methodology described in Appendix B.IV. The controls for these events take the form of binary indicator variables that indicate whether a reactor was under construction during a given event. I further allow a separate coefficient for the nations in which the accident occurred, namely the United States in the case of TMI and the Soviet Union in the case of Chernobyl.

Lastly, I control for whether the reactor is being built for an investor-owned or publicly-owned utility. Several possible hypotheses may point toward one form of ownership structure favoring faster or slower construction given the differing economic incentives, regulatory treatment, and cost of capital associated with each business model. My preferred hypothesis is that, given the higher cost of capital for investor-owned utilities, I expect that investor-owned utilities generally complete construction faster.

The econometric model is given by:

$$\begin{aligned} ln(LT_i) =& \beta_1 ln(GDPpc_{c,y}) + \beta_2 Dem_{c,y} + \beta_3 Dec_{c,y} \\ &+ \sum_{x \in X} \xi_{x,i} + \gamma_2 1\{IOU_i\} + \gamma_1 ln(\widehat{LT_i}) + \lambda_m + \varepsilon_i \end{aligned} \tag{5}$$

IV.C. Mechanism 3: Megaproject Syndrome

Megaprojects like nuclear power plants have a natural tendency toward schedule slippage. I theorize that political decentralization exacerbates megaproject syndrome by initiating more instances of scope change mid-construction and increasing the number of external stakeholders who may intervene in the project.

To quantitatively measure such an effect, I take as a measure of complexity and scale the variable $ln(\widehat{LT_i})$ generated from Step 1 of the analysis in Section IV.A. This variable primarily reflects the size of the reactor in megawatts, but it also incorporates several other specifications and design choices that are associated with longer or shorter lead times, such as whether the reactor is of a standardized design. I hypothesize that, if decentralization exacerbates megaproject syndrome, then the penalty to lead time arising from a higher degree of "megaproject-iness" should be stronger in decentralized nations. I model this with an interaction between $ln(\widehat{LT_i})$ and decentralization.

I build the econometric specification as follows. I include country fixed effects, as there is sufficient within-country dispersion in $ln(\widehat{LT_i})$ to generate well-powered estimates. These fixed effects control for differing national characteristics; cross-national differences in the level of LT are not of interest for this hypothesis. Next, I include year fixed effects as there is sufficient dispersion within years to generate well-powered estimates. This removes any global time trends in LT.

However, two-way fixed effects cannot account for the possibility that time trends differ by country for reasons unrelated to the interaction of $ln(\widehat{LT_i})$ and decentralization. While fixed effects by country-year would be ideal, the number of degrees of freedom would greatly diminish with the introduction of so many fixed effects. Furthermore, in 155 cases, there were no other reactors which began construction in the same country in the same year, so there is no dispersion in size within those country-year pairs. As a next-best control for the possibility of differential trends by country, I include instrumented indicator variables for events which likely had a disproportionate effect on a particular country (TMI in the United States, Chernobyl in the Soviet Union)[16] or which occurred in different countries at different points in time (regime change). I also control for GDP per capita, which exhibits differing time trends across countries.

I do not control for any design characteristics or measurement error M_i, as these variables are embedded in the value of $ln(\widehat{LT_i})$. I do control for whether a investor-owned or publicly-owned utility is building the reactor, for the same reasons as in Section IV.B. I test several specifications, so the equation that follows is of a generalized nature, allowing for several specifications of β:

$$ln(LT_i) = \beta ln(\widehat{LT_i}) + \gamma_1 ln(GDPpc_{c,y}) + \gamma_2 1\{IOU_i\} + \sum_{x \in X} \xi_{x,i} + \delta_f + \mu_c + \nu_t + \varepsilon_i \tag{6}$$

I test several specifications of β. In the first specification, β is simply a constant that estimates the global average relationship between "megaproject-iness" and lead time. In the next

---

[16] No reactors under construction as of 3/11/2011 have entered operation in Japan as of the time of writing, so the parameter cannot be estimated.

specification, I estimate separate values of β by geopolitical region, as defined in Section III.C. In the final specifications, I allow β to vary as a linear combination of a nation's democracy and decentralization. While my hypothesis concerns decentralization, the intensity of megaproject syndrome could just as well vary with the level of democracy as with decentralization. Therefore, I include both variables in estimating β.

IV.D. Modeling Mechanism 4: resetting the learning curve

I theorize that political decentralization inhibits learning-by-doing through regulatory instability, jurisdictional diversity, and electricity market fragmentation. These factor oblige firms to abandon gains from proceeding down an established learning curve and begin exploring the learning curve of a more novel design. To estimate this effect empirically, I propose an econometric specification that allows the learning rate to vary according to the degree of decentralization of a country's political institutions.

I operationalize cumulative experience as the inverse hyperbolic sine transformation of the count of reactors of the same family as reactor i that began construction prior to reactor i. Further details regarding the measurement of cumulative experience are available in Appendix B.V.

I distinguish between two possible dimensions along which experience may matter. The first is the *within* dimension: the effect of cumulative experience on lead time that results from continuing to build more reactors *within* the same family. The second is the *between* dimension: the effect of cumulative experience on lead time that results when choosing *between* families of reactors with differing levels of cumulative experience.

I argue that the between dimension contains information regarding "learning-by-searching" [78], as opposed to learning-by-doing. When utilities are deciding between different designs of NPP to build, they face choices ranging from experimental reactor designs of uncertain future potential to reactor from families with an established track record and large experience base to draw from. The more established design should, in expectation, present fewer challenges in the construction process—even if the less experienced design has a greater, long-term techno-economic potential [79]. In settings with weak, inefficient, or impeded learning-by-searching, the benefits to adopting a more established design should be less evident.

In both cases, the methods herein do not generate strong causal inference. They should be understood as descriptive partial associations between cumulative experience and lead time, holding constant several other factors that might otherwise explain the correlation between experience and lead time. In particular, because cumulative experience is endogenous—families that are inherently better for techno-economic reasons are liable to gain more experience—estimation along the between dimension is especially suspect. Improving causal inference is an opportunity for future research.

For the econometric specification to capture "within family" learning, I naturally include fixed effects by reactor family. This means the econometric model assumes there are constant, unexplained differences between the level of lead time across different reactor families. Next, I include country fixed effects.[17] Political factors may cause differences in the average level of LT across countries; these differences are investigated with the methods of Section IV.B but are not of interest here.

These fixed effects (45 in total) combine to form an econometric specification in which the only remaining variation to be explained is changes in LT over time, within families of reactors, controlling for cross-national average differences in the level of lead time. Fixed effects by year of construction start would sap the model of nearly all remaining variation. Instead, I control for the major events affecting the nuclear industry per the instrumental variables strategy laid out in Appendix B.IV.

In general, I do not control for design specifications in these regressions, because an important component of learning-by-doing is using the information gained to redesign the product better next time. Holding design constant would limit the estimated learning effects to only learning arising from repetition of of identical or nearly similar designs. That said, I make three exceptions in controlling for the following design specifications:

First, I control for rated power output in megawatts. The trend towards increasingly large reactors over time is unambiguous; furthermore, size tends to be correlated with a reactor family's cumulative experience. In a regression of size in megawatts on cumulative experience with year fixed effects (i.e. removing any time trends and only looking at cross-sectional variation), I find that a doubling of cumulative experience is associated with a 74 megawatt increase in the size of

---

[17] Where country is defined as the country in which construction began. E.g. the Soviet Union and Russia are two separate "countries" for this purpose. Reactors which began construction under the Soviet Union and finished after its collapse are coded as belonging to the Soviet Union.

a reactor ($t = 14.6$). In other words, new concepts for reactors are implemented at a small scale first and then gradually scaled up as experience accumulates.

Given the economic costs of long lead times, I must conclude that NPP designers are not deliberately choosing larger capacities for the sake of longer lead times. Instead, they are reportedly choosing larger capacities in order to reduce OCC. Berthélemy and Escobar Rangel [10] find a strong negative association between size and OCC when controlling for LT; in unreported regressions, I replicate that finding with the larger sample provided by Portugal-Pereira et al. [22]. However, given the likely causal effect of LT on OCC and the certain effect of LT on financing costs, this strategy of ever-increasing scale may not be wise.

Two additional design characteristics I control for are whether the reactor was used for co-production of electricity and plutonium and the cooling technology. I argue that reactors which co-produced electricity and plutonium exhibit exceptionally fast lead times because they were built in haste for military purposes during the Cold War. Regarding cooling technology, the use of once-through cooling or some other method to discharge waste heat is determined by environmental conditions and environmental regulations. Cooling towers are not unique to the nuclear industry.

As in Sections IV.B and IV.C, I control for whether the reactor is being built for an investor-owned or publicly-owned utility for the same reasons described there. Given the substantial within-country, over-time variation in GDP per capita, I control for it. Conversely, there is very little within-country, over-time variation in the level of democracy and decentralization in my sample, so I do not control for those. To summarize, the econometric specification for "within family" learning-by-doing is given by:

$$\begin{aligned} ln(LT_i) =& \beta sinh^{-1}(Exp_{i,f}) + \theta_1 MW_i + \theta_2 1\{OTC_i\} + \theta_3 1\{Pu_i\} + \sum_{x \in X} \xi_{x,i} \\ &+ \gamma_1 ln(GDPpc_{c,y}) + \gamma_2 1\{IOU_i\} + \gamma_3 M_i + \delta_f + \mu_c + \varepsilon_i \end{aligned} \tag{7}$$

Similar to the approach in Section IV.C, I allow β to vary across countries according to a linear combination of its political characteristics. I standardize $ln(GDPpc_{c,y})$, $Dem_{c,y}$, and $Dem_{c,y}$ such that they are centered on their global average values and scaled by their global standard deviations.[18]

---

[18] Global averages and standard deviations are computed from the global population of countries, not just those

To estimate the effects of cumulative experience when comparing between different families of reactors, the first step is to omit the family fixed effects. I retain the country fixed effects from before, as there is plenty of within-country dispersion in cumulative experience to work with. This time, I add year fixed across, so that the comparison is between different families of reactors with differing levels of experience at the same point in time. Year fixed effects render unnecessary most of the controls for major events affecting the nuclear industry, except those that may affect certain countries deferentially, as discussed in Section IV.C.

As with the "within family" estimation, I control for capacity in megawatts, plutonium co-production, investor-ownership, and GDP per capita. The econometric specification for "between family" learning-by-searching is given by:

$$\begin{aligned} ln(LT_i) =& \beta sinh^{-1}(Exp_{i,f}) + \theta_1 MW_i + \theta_2 1\{OTC_i\} + \theta_3 1\{Pu_i\} + \sum_{x \in X'} \xi_{x,i} \\ &+ \gamma_1 ln(GDPpc_{c,y}) + \gamma_2 1\{IOU_i\} + \gamma_3 M_i + \mu_c + \nu_t + \varepsilon_i \end{aligned} \tag{8}$$

V. RESULTS

V.A. Results for Mechanism 1: Politically Constrained Design

The regression of lead time on design specifications laid out in Equation 3 of Section IV.A was conducted, but it is not reported here to spare the reader a table with an extremely long list of regressors associated with several null results. Those seeking the entire regression output may find it in the online data appendix. In its place, a digest of the noteworthy results are presented in Table IV. These results are based on a regression which drops statistically or economically insignificant variables from the original, full specification in the interest of greater data coverage and parsimony of parameters. To be clear, all results presented elsewhere in this paper rely on the predicted values of LT that were generated from running the regression specified in Equation 3.

[Table IV about here]

I will contextualize and interpret some of the results Table IV for the benefit of readers not familiar with the technical terms related to nuclear reactor design.

---

which have built NPPs.

The relationship between power output and lead time was ascertained to be best approximated as log-linear through rigorous testing of alternative specifications. The estimated effect size implies that a typical 1GW reactor (which is the approximate order of magnitude as nearly all reactors being built today) would take 73.9% longer to build than a hypothetical 50 MW small modular reactor (SMR). For reference, the global average LT for gigawatt-scale reactors is around 86 months, so the basis of the scaling factor alone, the estimated lead time of the SMR would be 49.4 months. Further applying the bonus to standardized designs brings the estimate to around 41 months.

Temperature rise across the core (T) refers to the difference in temperature between the the primary coolant[19] upon exit from the reactor, minus its temperature upon entry. The median T is 35°C; the range is extremely wide, from a minimum of 3°C to a maximum of 690 °C. Hotter outlet temperatures enable greater thermal efficiency in the conversion of steam to electricity, but they also present greater safety challenges. The full regression finds that the impact of T on LT varies widely by type of reactor, so the result presented in IV should be interpreted with caution. Hotter outlet temperatures enable greater thermal efficiency in the conversion of steam to electricity, but they also present greater safety challenges.

The number of primary coolant loops[20] do not vary quite so widely, being typically between two and four, with a maximum observed value of 8. The results suggest that more loops represent more complexity to deal with in construction, but the effect sizes are not statistically significant. That said, in unreported regressions I there is a clear trend towards a reduction in the number of these loops, which is consistent with the idea of the industry trying to streamline design.

Once-through cooling (OTC) refers to the practice of discharging waste heat directly into a nearby body of water. This obviates the need for cooling towers or other structures designed to dissipate waste heat into the atmosphere; it also enhances the efficiency of the conversion of heat to electricity. There is a sizeable reduction in lead time associated with OTC, approximately 12.5%. In unreported regressions, no statistical difference was found when comparing natural draft to forced draft cooling towers; both add nearly the same amount to the construction schedule relative to OTC.

---

[19] The primary coolant is the fluid that conveys heat away from the core, where the heat is generated, to the remainder of the plant where it is converted to steam.

[20] These are the independent piping systems through which primary coolant flows

There are 25 reactors in the dataset which are coded as having been used both as plutonium production reactors and power reactors. These are all from the earliest days of the industry and were built by government agencies and state-owned utilities. The result in Table IV suggests that these nations made an exception effort to get these built as quickly as possible; the coefficient implies that were built effectively 3 times faster than an otherwise comparable reactor.

I find that reactors of standardized designs finish construction and commissioning 16.8% faster than their custom-built peers, on average. This strongly suggests that custom-ordering a nuclear power plant is generally a mistake, except perhaps for experimental purposes. To explore this further, I ran a logistic regression to understand the determinants of reactor standardization, the results of which are presented in Table V. At first, it appears that decentralized nations and investor-owned utilities are less likely to adopt standardized designs (as indicated by odds-ratios less than one). However, Column (4) reveals that this finding is probably an artefact of the fragmentation of the electricity sector in such countries, and not necessarily related to political conditions. I theorize that countries with more utilities fail to coordinate on a standardized design.

[Table V about here]

The predicted values of LT generated by the full regression of Equation 3 are displayed in Figure 4, where they graphed against the observed values of LT. The estimated slope coefficient is 0.726 (standard error = 0.081, N = 510). The low R^2 (22.6%) implies that observed design characteristics only account for a modest fraction of the overall global dispersion in lead times. Furthermore, I find predicted LT does not trend upward over time.[21] This is suggestive evidence for the view that the escalation over time in LT cannot be solely attributed to changes in design, whether arising from regulation or industry mismanagement. However, further research should revisit this question when more data concerning safety features can be collected.

[Figure 4 about here]

Table VI displays the results of the second stage of the analysis, wherein the fitted values of lead time (as predicted solely by design characteristics) are regressed on national characteristics. The only national characteristic meaningfully correlated with design-related lead time is GDP per

---

[21] A bivariate regression finds that predicted LT increased by less than 0.01% per year (p=0.897) over the sample period.

capita, and this correlation becomes statistically insignificant and economically marginal when controlling for the tendency of richer countries to build larger reactors. This is strong evidence against the hypothesis of "politically constrained design." That is to say, there is no evidence that democratic or decentralized nations exhibit longer LT in NPP construction on account of differences in the design of the plants as contrasted with those in undemocratic or centralized nations.

[Figure VI about here]

V.B. Results for Mechanism 2: Regulatory Delays

In Table VII, I report the results of Equation 5. The results provide reasonable confidence in the hypothesis that decentralization is associated with slower NPP construction, holding all else constant. However, the effect sizes are fairly modest. A federalist constitutional design is associated with 22% longer lead times, relative to unitary constitutions. The range of values in the continuous measures of decentralization spans approximately three standard deviations, so the comparable effect size from Column (2) and Column (3) would be on the order of a 27% increase. A 3-S.D. increase in decentralization is equivalent to the difference between federalism in the United States and the centralism in Finland present in the 1970s.[22]

[Table VII about here]

Table VII also present results of the estimated effect on lead time arising from various events that impacted the politics and regulation of the nuclear industry. As these are not central to the present work, I will not discuss them at length. However, I will note a few issues that likely undermine the accuracy of the estimates. First, the finding that the Chernobyl disaster supposedly accelerated NPP construction in the USSR is almost surely spurious. Being under construction during the Chernobyl disaster in the USSR is correlated with being under construction during regime change, as the fall of communism occurred a few years later. The combined effect of both events is roughly a 25%[23] increase in LT. Soviet NPPs which were under construction on 4/26/1986 but still finished construction prior to 1991 represent those which began their construction relatively

---

[22] Disregard the special autonomous status of the Åland Islands, where no NPPs have been built.

[23] $4.2\% - 30.4\% + 51.5\%$

earlier (recall that Eq. 5 includes no year fixed effects) and therefore were closer to completing construction sooner, thereby avoiding the upheaval of the 1990s.

Regarding the Fukushima Daiichi disaster, only reactors which have entered operation as of Septemper 25, 2020 are included in the sample, so the coefficient is necessarily biased downwards by the exclusion of reactors with longer lead times.

V.C. Results for Mechanism 3: Megaproject Syndrome

Table VIII displays the results of regressions which test the hypothesis that there is a cost to greater scale and complexity of NPPs in the form of a longer lead time, and moreover, that cost varies across countries. Column (1) reports the finding that, globally on average, the correspondence between a reactor's predicted LT and its actual LT is fairly close to a one-to-one relationship.[24] In Columns (2), (3), and (4), I allow the parameter governing this relationship to vary according to national political characteristics. A role of democracy is exceptionally precisely rejected in Column (2), although Columns (3) and (4) report less precise findings. Considering the negative sign, small magnitude, and statistical insignificance of all three estimates, I consider it unlikely that democracy governs this relationship.

Concerning decentralization, if it mediates "megaproject syndrome," then a federal constitution is an insufficiently precise measure of decentralization to capture that effect. Columns (3) and (4), which rely on continuous measures, suggests with some confidence that political decentralization is associated with more pronounced diseconomies of scale in NPP construction. That is to say, there is positive relationship between scale and lead time, and that relationship is even more positive in the most decentralized countries, while it is less so in centralized countries. Note that the $Dem_{c,y}$ and $Dec_{c,y}$ variables are standardized according to their z-values, so they are centered on the global averages. Thus, the uninteracted coefficient on $\widehat{LT_i}$ can be interpreted as the marginal effect in a country with average values of both variables.[25]

[Table VIII about here]

---

[24] The upper bound of the 95% confidence interval is 1.024.

[25] There is one exception, namely in Column (2). Having a federal constitution is not normalized; it is a binary variable. The interpretation of the uninteracted coefficient is that of the marginal effect in nations with unitary constitutions.

Column (5) allows for the relationship between $\widehat{LT_i}$ and LT_i to vary according to geopolitical regions. The precise meaning of each of these regions is defined and justified in Appendix A.II. Some interesting patterns emerge, although I will note that the only coefficient which statistically differs from one[26] is the coefficient for East Asia ($t = 3.73$). It appears that East Asian countries—Mainland China, Taiwan, South Korea, and Japan—are exceptionally competent at managing large and complex NPP construction projects, much more so than the rest of the world. This may have something to do with their highly unitary political regimes, although surely that is not the only factor at play. It should not go without mention that all three of Western–aligned East Asian nations began their NPP programs under eras of weak or absent democratic institutions involving rule by military dictatorships (e.g. Park Chung-hee, in South Korea) or a single political party (KMT in Taiwan, LDP in Japan). The increasing political contestation of nuclear power policy in these now firmly democratic nations might dismantle the conditions that made their earlier NPP deployments so successful. However, if democracy matters, the present methods are not sufficient to identify any such effect.

V.D. Results for Mechanism 4: resetting the learning curve

Table IX displays the results of regressions estimating the effect of cumulative experience on lead time. Columns (1), (2), and (3) report the raw parameters that form a linear combination in estimating β in Equation 7. Recall that this equation is designed to capture learning-by-doing within reactor families by examining trends in LT, holding constant any level effect of the reactor family. Conversely, Columns (4), (5), and (6) the raw parameters that form a linear combination in estimating β in Equation 8. Recall that this equation is designed to capture learning-by-searching across reactor families by how reactor families with more experience fare in terms of LT relative to those with less experience, at a fixed year in history.

Because variables $Dem_{c,y}$ and $Dec_{c,y}$ are standardized according to their z-values, the uninteracted coefficients can be interpreted as the marginal effect in a country with average values of both variables.[27] The estimated learning-by-doing rate is not statistically different from zero in the

---

[26] The t-statistics in Table VIII refer to the coefficient's statistical difference from zero.

[27] This is with the exception of Columns (1) and (4), as having a federal constitution is not normalized; it is a binary variable. The interpretation of the uninteracted coefficient is that of the marginal effect in nations with unitary constitutions.

average nation, whereas the benefit of learning-by-search appears to be considerable. Averaging the three results in Columns (4) through (6) and transforming them according to Equation 1 implies a learning-by-searching rate of 7.6%. The interpretation of such a learning rate is as follows: Consider two reactors from two different reactor families that are built in otherwise identical national conditions at the same point in time. The reactor A's family has a cumulative experience double that of reactor B's family. Holding all else equal, we expect the reactor A to finish construction 7.6% faster than reactor B. This may be because the family of reactor A is technically superior (which is why it has accumulated more experience) or it may be because the greater experience base, which facilitates more timely construction. Future research could try to establish causal identification along this "between" dimension.

When we examine the interaction terms and consider how these estimated learning rates vary according to political conditions, the picture is considerably different. Columns (2) and (3) present statistically significant evidence for the hypothesis that learning-by-doing does not operate as efficiently in politically decentralised nations. Indeed, the estimated coefficients imply a learning-by-doing rate of 1.1% in a nation like China with decentralization roughly one standard deviation below the global but a rate of -5.5% in a nation like the United States with decentralization two standard deviations above the mean. To put these values in perspective, consider the reactor family with the largest cumulative experience, Westinghouse PWRs, which includes reactors that trace their evolutionary origins to Westinghouse's original technology.[28] The global installed base of the Westinghouse family, as of the commencement on construction on Vogtle 3 in the United States, was 246 reactors.[29] This constitutes nearly 8[30] doublings of cumulative deployment. At learning-by-doing rate of -5.5%, the resulting increase in lead time arising from "forgetting-by-doing" is on the order of 50%.[31] Conversely, a learning-by-doing rate of -1.1% would result in a cumulative reduction of LT by around 8%.

Columns (5) and (6) exhibit qualitatively similar results regarding the mediating role of political decentralization. However, the magnitudes of the coefficients are small and the t-values are clearly below conventional levels of statistical significance. Therefore, in the context of learning-

---

[28] See Appendix A.I for the definition of reactor families.

[29] Author's own calculations per the definition of reactor family used in this study. See the online data appendix for tabulation and further calculations.

[30] $log_2(246) \approx 7.94$

[31] $[1-(-0.055)]^{7.94}) \approx = 0.533$

by-searching, the hypothesis that decentralization interferes with learning is not supported.

[Table IX about here]

VI. CONCLUSION

VI.A. Discussion

This paper hypothesized and investigated several mechanisms by which decentralization influences the lead times of nuclear power plants. The findings are as follows:

The design specifications of NPPs, in so far as they relate to lead time, do not appear to be correlated with political factors. Richer countries have a tendency to build larger reactors. Decentralized countries have a higher propensity to build reactors of a non-standardized design, but this association is explained by their higher levels of electricity market fragmentation. Without a single national electric utility, coordination on a standardized design tends not to happen, except by explicit national policy, as in Japan.

Conditional on observed design specifications, I find that otherwise identical NPPs tend to take longer to build in politically decentralized nations. This result is similar in spirit to recent work by Brooks and Liscow [80], who document a three-fold increase in real highway construction costs per mile in the United States and argue that it "coincides with the rise of 'citizen voice' in government decision-making in the early 1970s." So-called "freeway revolts" and mass movement politics against nuclear power engaged in political messaging with similar themes, including citizen participation, local control, and a "not in my backyard" ethos [60]. However, further research is needed to improve the data coverage of safety-related technical characteristics of NPPs to ensure that the comparison is truly between "otherwise identical" NPPs.

I find strong evidence for the hypothesis that decentralization sharpens the diseconomies of scale for NPP lead times. In other words, bigger plants take longer to build, and in decentralized nations, this positive relationship is even steeper. However, given the tendency of nuclear reactors to get bigger as firms accumulate experience with related designs of reactors, the econometric methods employed herein leave it ambiguous whether "megaproject syndrome" or "resetting the learning curve" is a better explanation for the observed patterns in the data.

The difference in the average learning-by-doing rate (effectively zero) and the average learning-by-searching rate (modest, but statistically significant and indicative of beneficial learning) merits some comment. The cross-sectional dimension and the time-dimension of the cumulative experience, as I have defined it, may reflect two different underlying data-generating processes. Over time, as more is learned about the technology of a reactor family, additional time-intensive measures become necessary to implement in reactor design in order satisfy new safety requirements or perhaps to improve operational reliability of the plant. This may be for reasons that simply trend upwards over time that are unrelated to learning about a specific technology, or perhaps it is a byproduct of learning. Empirically, I find increasing lead time for reactors built in decentralized nations as experience accumulates within reactor families, but no such effect in centralized nations. This is suggestive of a political explanation.

Conversely, at a given point in time, I find that there are clear gains to be had from choosing reactor families with more experience as opposed to less. If we suppose that political factors (like local opposition) are not sensitive to the details of the design of the plant, then it follows that such a relationship between experience and LT on the between dimension will not be mediated by political factors (which is what I have found empirically). I will conjecture, in absence of any evidence presented here, that local opposition to NPPs is generally not sensitive to the details of the design of a particular NPP and is instead motivated by generic concerns about the safety and sustainability of nuclear power.

Advocates of SMRs will find much to cheer in my work, as there are clear benefits to small size and standardized design with respect to lead time. Applying both the estimated scaling factor and the bonus from design standardization based on the result of Table IV, it can be conjectured that a 50 MW reactor of standardized design could achieve lead times on the order of 41 months. Such a lead time would go a long way toward improving the economics of NPP construction.

VI.B. Directions for Future Research

I see several opportunities for extending and improving this area of research. Most immediately, one could extend the present work by modeling the simultaneous determination of OCC and LT as in Berthélemy and Escobar Rangel [10] while using the large sample of OCC data compiled by Portugal-Pereira et al. [22]. This would be important for determining the extent to which decentralization drives up OCC as a consequence of longer LT, or if it impacts OCC directly.

A more clean-cut test of the "logic of local democratic control" would require direct measurements of the intensity of local opposition and regulatory burden on individual NPP construction projects. Berndt and Aldrich [61] rely on a novel measure of regulatory burden for proposed and under-construction NPPs in the United States, namely the number of new regulatory guides (or revisions thereto) published by the staff of the U.S. Atomic Energy Commission / Nuclear Regulatory Commission in the course of permitting and construction. Comparable measures of regulatory burden appropriate to the regulatory context of other nations would be desirable to improve the generalizability of findings.

The present work has largely taken the reactor family and the reactor model—as defined by the NSSS—as the primary unit of categorizing similar designs. However, NPPs consist of several other important features, such as the containment, the turbo-generator, and the balance-of-plant (BOP). Study of learning by firms involved other aspects of plant design and construction, such as the architect-engineer, the turbo-generator supplier, and the constructor could be another fruitful area for investigation. Berthélemy and Escobar Rangel [10] show a clear role for the architect-engineer in learning, but the sample is limited to a handful of countries. More data collection on the identity of these firms could expand the analysis to the global population.

The results of Table IV confirm past findings and conventional wisdom among industry observers that reactor standardization improves the economics of NPP construction. While I show that fragmentation of the electricity market is associated with non-standardization, the issue would benefit from more formal modeling of the decision to standardize. Indeed, why do firms ever redesign NPPs given the heavy upfront development and licensing costs? The answer surely involves regulation and learning, but there are likely to be industrial organization explanations for why customization was so historically prevalent in the U.S. nuclear industry.

The findings from the present work could have implications for other types of large construction projects that are known to suffer from megaproject syndrome. The customized nature of most megaprojects is comparable to the lack of standardization that historically plagued NPP construction. Furthermore, many types of megaprojects are also liable to attract local opposition. The present work found that decentralisation increases the lead time penalties arising from the complexity and scale of an NPP. This could be interpreted as decentralization having the effect of intensifying megaproject syndrome. Future extensions of this work could examine other types of power plants and even infrastructure outside the electricity sector to see whether the pattern found here extends to those settings.

ACKNOWLEDGMENTS

This research was supported in part with funding from the UC Irvine Department of Economics.

Special thanks are owed to the IAEA for access to restricted data, and to Linda Cohen, Ami Glazer, Damon Clark, Stergios Skaperdas, Dan Bogart, Tony Smith, Aditi Verma, Richard DiSalvo, and three anonymous reviewers for detailed comments. I offer the standard disclaimer that any remaining errors are my own.

REFERENCES

[1] Arnulf Grubler. The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy*, 38(9):5174–5188, 2010.

[2] Benjamin K Sovacool, Alex Gilbert, and Daniel Nugent. Risk, innovation, electricity infrastructure and construction cost overruns: Testing six hypotheses. *Energy*, 74:906–917, 2014.

[3] Edward S Rubin, Inês ML Azevedo, Paulina Jaramillo, and Sonia Yeh. A review of learning rates for electricity supply technologies. *Energy Policy*, 86:198–218, 2015.

[4] Bent Flyvbjerg, Nils Bruzelius, Werner Rothengatter, et al. *Megaprojects and risk: An anatomy of ambition*. Cambridge University Press, 2003.

[5] Edward Shyloski. What Went Wrong on the Westinghouse Nuclear Projects. *Engineering News-Record*, 2017. https://www.enr.com/articles/41869-what-went-wrong-on-the-westinghouse-nuclear-projects Accessed September 25, 2020.

[6] Charles Komanoff. *Power Plant Cost Escalation: nuclear and coal capital costs, regulation, and economics*. Van Norstrand Reinhold Company, 1981.

[7] Zsuzsanna Csereklyei, Paul W Thurner, Alexander Bauer, and Helmut Küchenhoff. The effect of economic growth, oil prices, and the benefits of reactor standardization: duration of nuclear power plant construction revisited". *Energy Policy*, 91:49–59, 2016.

[8] Kristy Gogan, Eric Ingersoll, Andrew Foss, and John Herter. The eti nuclear cost drivers project: Summary report. 2018. https://www.eti.co.uk/library/the-eti-nuclear-cost-drivers-project-summary-report.

[9] Rod Adams. Economy of Scale? Is Bigger Better? *Atomic Insights*, 1996. https://atomicinsights.com/economy-of-scale-bigger-better/.

[10] Michel Berthélemy and Lina Escobar Rangel. Nuclear reactors' construction costs: the role of lead-time, standardization and technological progress. *Energy Policy*, 82:118–130, 2015.

[11] Jessica R Lovering, Arthur Yip, and Ted Nordhaus. Historical Construction Costs of Global Nuclear Power Reactors. *Energy Policy*, 91:371–382, 2016.

[12] Jonathan Koomey, Nathan E Hultman, and Arnulf Grubler. A reply to 'historical construction costs of global nuclear power reactors'. *Energy Policy*, 102:640–643, 2017.

[13] Alexander Gilbert, Benjamin K Sovacool, Phil Johnstone, and Andy Stirling. Cost overruns and financial risk in the construction of nuclear power reactors: A critical appraisal. *Energy Policy*, 102:644–649, 2017.

[14] Jessica R Lovering, Ted Nordhaus, and Arthur Yip. Apples and oranges: Comparing nuclear construction costs across nations, time periods, and technologies. *Energy Policy*, 102:650–654, 2017.

[15] Mancur Olson. *The Logic of Collective Action*. Harvard University Press, 1965. ISBN 9780674537514.

[16] Bent Flyvbjerg, Mette Skamris Holm, and Soren Buhl. Underestimating costs in public works projects: Error or lie? *Journal of the American planning association*, 68(3):279–295, 2002.

[17] International Atomic Energy Agency. Nuclear power reactors in the world (reference data series no. 2). https://www.iaea.org/publications/13552/nuclear-power-reactors-in-the-world, year=2019.

[18] Energy Options Network. What will advanced nuclear power plants cost?, 2017. https://www.innovationreform.org/wp-content/uploads/2018/01/Advanced-Nuclear-Reactors-Cost-Study.pdf Accessed September 25, 2020.

[19] Geoffrey Rothwell. *Economics of Nuclear Power*. Routledge, 2016.

[20] Jonathan Koomey and Nathan E Hultman. A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005. *Energy Policy*, 35(11):5630–5642, 2007.

[21] Lina Escobar Rangel and FranÇois Lévêque. Revisiting the cost escalation curse of nuclear power: New lessons from the french experience. *Economics of Energy & Environmental Policy*, 4(2):103–126, 2015.

[22] J Portugal-Pereira, P Ferreira, J Cunha, A Szklo, R Schaeffer, and M Araújo. Better late than never, but never late is better: Risk assessment of nuclear power construction projects. *Energy Policy*, 120:158–166, 2018.

[23] Benjamin K Sovacool, Alex Gilbert, and Daniel Nugent. An international comparative assessment of construction cost overruns for electricity infrastructure. *Energy Research & Social Science*, 3:152–160, 2014.

[24] Benjamin K Sovacool, Daniel Nugent, and Alex Gilbert. Construction cost overruns and electricity infrastructure: an unavoidable risk? *The Electricity Journal*, 27(4):112–120, 2014.

[25] United Engineers and Constructors. Energy economic data base program (eedb-viii): Phase viii update (1986) report. Technical report, 1986. `https://www.osti.gov/servlets/purl/6927146/`.

[26] Kenneth J Arrow. The economic implications of learning by doing. *Review of Economic Studies*, 29(3):155–173, 1962.

[27] Theodore P Wright. Factors affecting the cost of airplanes. *Journal of the aeronautical sciences*, 3(4):122–128, 1936.

[28] Paul L Joskow and George A Rozanski. The effects of learning by doing on nuclear plant operating reliability. *The Review of Economics and Statistics*, pages 161–168, 1979.

[29] Lucas W Davis and Catherine Wolfram. Deregulation, consolidation, and efficiency: Evidence from us nuclear power. *American Economic Journal: Applied Economics*, 4(4):194–225, 2012.

[30] United States Nuclear Regulatory Commission. Power uprates for nuclear plants, 2018. `https://www.nrc.gov/docs/ML0311/ML031120472.pdf`.

[31] T.A. Brock, M.N. Nguyen, D.A. Hagemeyer, and D.B. Holcomb. Occupational radiation exposure at commercial nuclear power reactors and other facilities 2018: Fifty-first annual report (nureg-0713, volume 40). Technical report, United States Nuclear Regulatory Commission, 2020. `https://www.nrc.gov/docs/ML2008/ML20087J424.pdf`.

[32] Nancy Johnson and John A Schroeder. Initiating event rates at us nuclear power plants: 1988–2016. Technical report, Idaho National Laboratory, 2017.

[33] T Wiesenthal, P Dowling, J Morbee, C Thiel, B Schade, P Russ, S Simoes, S Peteves, K Schoots, M Londo, et al. Technology learning curves for energy policy support. *JRC scientific and policy reports*, 332, 2012.

[34] Nikolaos Kouvaritakis, Antonio Soria, and Stephane Isoard. Modelling energy technology dynamics: methodology for adaptive expectations models with learning by doing and learning by searching. *International Journal of Global Energy Issues*, 14(1-4):104–115, 2000.

[35] Jan Mischke Robert Palter Gernot Strube Nick Bertram, Steffen Fuchs and Jonathan Woetzel. Modular construction: from projects to products. Technical report, 2019. `https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/modular-construction-from-projects-to-products`.

[36] Simon Philipps and Werner Warmuth. Photovoltaics report. Technical report, 2020. `https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html` Last updated June 23, 2020.

[37] Amro M Elshurafa, Shahad R Albardi, Simona Bigerna, and Carlo Andrea Bollino. Estimating the learning curve of solar pv balance–of–system for over 20 countries: Implications and policy recommendations. *Journal of Cleaner Production*, 196:122–134, 2018.

[38] Daniel T Ingersoll. Deliberately small reactors and the second nuclear era. *Progress in nuclear energy*, 51(4-5):589–603, 2009.

[39] General Electric. Aeroderivative and heavy duty gas turbines, 2020. `https://www.ge.com/power/gas/gas-turbines` Accessed September 25, 2020.

[40] Sonal Patel. A brief history of ge gas turbines, 2019. `https://www.powermag.com/a-brief-history-of-ge-gas-turbines-2/`.

[41] Mirela Gavrilas, Pavel Hejzlar, Neil E. Todreas, and Youssef Shatilla. *Safety Features of Operating Light Water Reactors of Western Design.* CRC Press, 1995.

[42] Paul A David and Geoffrey S Rothwell. Standardization, diversity and learning: Strategies for the coevolution of technology and industrial capacity. *International Journal of Industrial Organization*, 14(2):181–201, 1996.

[43] Soon Paik and William R Schriver. The effect of increased regulation on capital costs and manual labor requirements of nuclear power plants. *The Engineering Economist*, 26(3):223–244, 1980.

[44] Alfons Van Marrewijk, Stewart R Clegg, Tyrone S Pitsis, and Marcel Veenswijk. Managing public–private megaprojects: Paradoxes, complexity, and project design. *International journal of project management*, 26(6):591–600, 2008.

[45] Edward W Merrow. *Industrial Megaprojects.* Wiley, 2011.

[46] Bent Flyvbjerg. What you should know about megaprojects and why: An overview. *Project management journal*, 45(2):6–19, 2014.

[47] Virginia A Greiman. *Megaproject management: Lessons on risk and project management from the Big Dig.* John Wiley & Sons, 2013.

[48] Giorgio Locatelli, Giacomo Mariani, Tristano Sainati, and Marco Greco. Corruption in public projects and megaprojects: There is an elephant in the room! *International Journal of Project Management*, 35(3):252–268, 2017.

[49] Sylvain Lenfle and Christophe Loch. Has megaproject management lost its way? In Bent Flyvbjerg, editor, *The Oxford handbook of megaproject management*, chapter 2, pages 21–38. Oxford University Press, 2017.

[50] Stefan Olander and Anne Landin. A comparative study of factors affecting the external stakeholder management process. *Construction management and economics*, 26(6):553–561, 2008.

[51] Pranab Bardhan. Decentralization of Governance and Development. *Journal of Economic perspectives*, 16(4):185–205, 2002.

[52] Jean-Paul Faguet and Caroline Pöschl. *Is decentralization good for development?: Perspectives from academics and policy makers.* Oxford University Press, USA, 2015.

[53] Jorge Martinez-Vazquez, Santiago Lago-Peñas, and Agnese Sacchi. The impact of fiscal decentralization: A survey. *Journal of Economic Surveys*, 31(4):1095–1129, 2017.

[54] Antonis Adam, Manthos D Delis, and Pantelis Kammas. Fiscal decentralization and public sector efficiency: evidence from oecd countries. *Economics of Governance*, 15(1):17–49, 2014.

[55] Arun Agrawal. Accountability in Decentralization: A Framework with South Asian and West African Cases. *The Journal of Developing Areas*, 33(4):473–502, 1999.

[56] Christian Lessmann and Gunther Markwardt. One size fits all? decentralization, corruption, and the monitoring of bureaucrats. *World Development*, 38(4):631–646, 2010.

[57] Timothy Besley and Anne Case. Incumbent behavior: Vote-seeking, tax-setting, and yardstick competition. *American Economic Review*, 1995.

[58] Barry R Weingast. The economic role of political institutions: Market-preserving federalism and economic development. *Journal of Law, Economics, & Organization*, pages 1–31, 1995.

[59] Christian Joppke. Decentralization of control in us nuclear energy policy. *Political Science Quarterly*, 107(4):709–725, 1992.

[60] Thomas Raymond Wellock. *Critical Masses: Opposition to Nuclear Power in California, 1958-1978.* University of Wisconsin Press, 1998.

[61] Eric Berndt and Daniel P Aldrich. Power to the people or regulatory ratcheting? explaining the success (or failure) of attempts to site commercial us nuclear power plants: 1954–1996. *International Journal of Energy Research*, 40(7):903–923, 2016.

[62] Daniel P. Aldrich. *Site fights: Divisive facilities and civil society in Japan and the West.* Cornell University Press, 2010.

[63] John Surrey and Charlotte Huggett. Opposition to nuclear power: A review of international experience. *Energy Policy*, 4(4):286–307, 1976.

[64] Ian Welsh. The nimby syndrome: its significance in the history of the nuclear debate in britain. *The British Journal for the History of Science*, 26(1):15–32, 1993.

[65] Mark J Kurlansky. International: Separatists and nuclear power. *Environment: Science and Policy for Sustainable Development*, 23(1):2–4, 1981.

[66] Jane I Dawson. Anti-nuclear activism in the ussr and its successor states: A surrogate for nationalism? *Environmental Politics*, 4(3):441–466, 1995.

[67] Kate Burningham. Using the language of nimby: a topic for research, not an activity for researchers. *Local environment*, 5(1):55–67, 2000.

[68] Linda Cohen, Mathew McCubbins, and Frances Rosenbluth. The Politics of Nuclear Power in Japan and the United States. In Peter F Cowhey and Mathew McCubbins, editors, *Structure and Policy in Japan and the United States*, pages 177–202. Cambridge University Press, 1995.

[69] Magali Delmas and Bruce Heiman. Government credible commitment to the french and american nuclear power industries. *Journal of Policy Analysis and Management: The Journal of the Association for Public Policy Analysis and Management*, 20(3):433–456, 2001.

[70] Benjamin K Sovacool and Scott Victor Valentine. The socio-political economy of nuclear energy in China and India. *Energy*, 35(9):3803–3813, 2010.

[71] Benjamin K Sovacool and Scott Victor Valentine. The socio-political economy of nuclear power development in Japan and South Korea. *Energy Policy*, 38(12):7971–7979, 2010.

[72] Power Technology, None given.

[73] Pushker A Kharecha and James E Hansen. Prevented mortality and greenhouse gas emissions from historical and projected nuclear power. *Environmental science & technology*, 47(9): 4889–4895, 2013.

[74] Jutta Bolt, Robert Inklaar, Herman de Jong, and Jan Luiten van Zanden. Maddison Project Database, Version 2018. 2018. `https://www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2018`.

[75] Michael Coppedge, John Gerring, Carl Henrik Knutsen, Staffan I. Lindberg, Jan Teorell, David Altman, Michael Bernhard, M. Steven Fish, Adam Glynn, Allen Hicken, Anna

Lührmann, Kyle L. Marquardt, Kelly McMann, Pamela Paxton, Daniel Pemstein, Brigitte Seim, Rachel Sigman, Svend-Erik Skaaning, Jeffrey Staton, Steven Wilson, Agnes Cornell, Lisa Gastaldi, Haakon Gjerløw, Nina Ilchenko, Joshua Krusell, Laura Maxwell, Valeriya Mechkova, Juraj Medzihorsky, Josefine Pernes, and Johannes von R¨o. V-Dem Country-Year Dataset v9. Varieties of Democracy (V-Dem) Project. 2019.

[76] Daron Acemoglu and James A Robinson. *Why nations fail: The origins of power, prosperity, and poverty.* Crown, 2012.

[77] Sergio Correia. Singletons, cluster-robust standard errors and fixed effects: A bad mix. `http://scorreia.com/research/singletons.pdf`, 2015.

[78] Wesley M Cohen and Daniel A Levinthal. Innovation and learning: the two faces of r & d. *The economic journal*, 99(397):569–596, 1989.

[79] Robin Cowan. Nuclear power reactors: a study in technological lock-in. *The journal of economic history*, 50(3):541–567, 1990.

[80] Leah Brooks and Zachary D Liscow. Infrastructure costs. 2019. `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3428675`.

[81] Viktor A Sidorenko. Nuclear power in the Soviet Union and in Russia. *Nuclear engineering and design*, 173(1-3):3–20, 1997.

[82] William J Garland, editor. *The Essential CANDU, A Textbook on the CANDU Nuclear Power Plant Technology.* University Network of Excellence in Nuclear Engineering, 2016. `https://www.unene.ca/education/candu-textbook`.

[83] Stephen Goldberg and Robert Rosner. Nuclear reactors: Generation to generation. American academy of Arts and Sciences, 2011.

[84] Monty G. Marshall, Tedd Robert Gurr, and Keith Jaggers. Polity IV project: political regime characteristics and transitions 1900–2017. 2018. `http://www.systemicpeace.org/inscrdata.html` accessed April 1, 2019.

[85] Liesbet Hooghe, Gary Marks, Arjan H Schakel, Sara Niedzwiecki, Sandra Chapman Osterkatz, and Sarah Shair-Rosenfield. *Measuring Regional Authority.* Oxford University Press Oxford, UK, 2016.

[86] Jason P Sorens. Secession risk and fiscal federalism. *Publius: The Journal of Federalism*, 46 (1):25–50, 2015.

[87] James J Heckman. The common structure of statistical models of truncation, sample selection and limited dependent variables and a simple estimator for such models. In *Annals of Economic and Social Measurement, Volume 5, number 4*, pages 475–492. NBER, 1976.

[88] John B Burbidge, Lonnie Magee, and A Leslie Robb. Alternative transformations to handle extreme values of the dependent variable. *Journal of the American Statistical Association*, 83 (401):123–127, 1988.

[89] Marc F Bellemare and Casey J Wichman. Elasticities and the inverse hyperbolic sine transformation. *Oxford Bulletin of Economics and Statistics*, 2019.

A. DATA APPENDIX

The IAEA PRIS database consisted of 1,056 observations (reactors) as of the month of access (July 2018). Reactors listed as “in planning” or “cancelled planning” were excluded from all further analysis. In general, reactors serving experimental and research purposes were retained in the dataset so long as their primary experimental purpose was as prototypes for the design and operation of subsequent commercial NPPs (as opposed to testing facilities for nuclear materials or production of medical isotopes). Reactors serving dual purposes of commercial electricity generation and plutonium production for weapons were also retained; I generated a binary indicator of this feature of a reactor’s design and operation. Although they are meaningfully different from most of the sample in terms of scale and design, such reactors were retained in the sample to ensure accurate measurement of cumulative experience.

Therefore, the final data set consists of 774 observations (reactors) at 335 sites (power plants) in 43 countries (as defined by their present-day boundaries). Of these, 636 began commercial operation prior to September 25, 2020 and therefore have a computable lead time, which is the primary outcome of interest. Those whose construction was abandoned or is still underway as of the time of writing are included in analyses for which the dependent variable is not lead time.

Because the data in PRIS were provided by the owner of the NPP in question or by a governmental representative of the country in which it is located, PRIS suffers from internal inconsistencies in the coding of many of its variables. I employed my knowledge of the subject matter to clean up the data where an inconsistency was obvious. For example, Framatome changed its name to Areva during a restructuring in 2001, only to later change it back in 2018 after another restructuring. Reactors designed and manufactured by this company are not consistently labeled under a single name in the raw PRIS dataset. Similarly, I treat Rosatom—Rusia's state-owned monopoly in nuclear power plant construction and operation—as one-in-the-same firm as the Soviet Ministry of Medium Machine-Building, which was responsible for the Soviet nuclear power program. Rosatom came about through a series of restructurings after Chernobyl and the collapse of the Soviet Union. Rosatom retains the intellectual property and the Soviet manufacturing infrastructure related to nuclear power in Russian territory; it even occupies the same headquarters in Moscow as the old Soviet ministry.

Additionally, missing data is a pervasive problem in the raw PRIS dataset. Where possible, I filled in missing data by referring to publications in nuclear engineering journals and documents released by nuclear regulatory agencies. In a handful of cases, missing data concerning particular reactors were supplied directly to me by personal contacts[32] in the nuclear industry. Publications and other sources relied upon to supplement PRIS will be made available in a forthcoming online repository.

A.I. Sources, Cleaning, and Coding of Reactor-Level Variables

Site: In a handful of cases, I merged sites listed separately in PRIS into a single site that better reflects the co-location of certain reactors. For example, PRIS lists the site for the Shippingport Atomic Power Station as "Shippingport" and the site for Beaver Valley Units 1 and 2 as "Beaver Valley." Given that all three reactors were built immediately adjacent to each other, I edited the Shippingport reactor's site to "Beaver Valley" to unify all three reactors with a single coding.

---

[32] Thanks, Dad.

Country: Construction of the first observation in the dataset commenced in 1951, and several major changes in international borders have occurred since that time. For the purposes of the analysis, a reactor's "country" is whichever country had territorial sovereignty over its site as of the year construction begins. In particular, this means several reactors which began construction under the Soviet Union and Czechoslovakia but were finished after the dissolution of those countries are considered to be "in" those countries. However, in post-Soviet countries, work on fourteen new reactors has begun, twelve in Russia and two in Belarus. For the purposes of country fixed effects and standard errors clustered by country, Russia, Belarus, and the Soviet Union are treated as separate countries.

Net Lead Time: The dates of construction start, first criticality, first grid connection, and the first day of commercial operation are provided by PRIS. Construction start refers to the date on which concrete was poured for the foundation of the plant. First criticality represents an important step in the commissioning phase; it is the day on which atoms are first split by the plant. First grid connection refers to the first day on which any electricity is transmitted to the grid. A date of commercial operation is typically declared by the owner after all commissioning is complete and the plant is now ready to operate for commercial purposes. I compute gross lead time as the difference in days between the date of construction start and the date of commercial operation.

For plants that were suspended and later finished, I consulted articles in *Nucleonics Week* to identify the dates of suspension and resumption. The months during which a plant was suspended was subtracted from gross lead time—the months between construction start and commercial operation–to generate net lead time. To account for the problems arising from suspension of construction, I retain an indicator variable that takes on the value one for reactors which were suspended and a continuous measure of the number of months during which construction was suspended.[33] However, because there is reason to suspect that the decision to suspend construction is at least partly influenced by poor economics in construction, in the regressions reported above, I do not control for construction suspension.

---

[33] In unreported regressions, I find that—after subtracting the months of suspension from the gross lead time—the length of the suspension period has no statistically significant marginal effect on net lead time over and above the predictive power of a binary indicator of whether construction was ever temporarily suspended for any length of time.

In the main body of the paper, I use net lead time, but I refer to it as "lead time" or LT, for brevity. I wish to emphasize that *net* lead time is not intended to represent a "complete" measure of lead time for the purposes such as estimating LCOE or comparing the lead times of NPPs to the lead times of other technologies. *Gross* lead time, including periods of construction suspension, is the appropriate metric for those purposes. It may also be desireable to include planning and permitting phases, as in Aldrich [62], for certain purposes. My purpose in defining lead time in this way is to generate an outcome metric that improves apples-to-apples comparisons of NPPs in order to understand why LT varies cross-nationally and over time. It would be unfair to compare to compare on the basis of gross lead time, for example, French and Soviet PWRs that began construction in 1980s. Many Soviet NPP projects were put on hiatus for macroeconomic and political reasons. If policymakers and industry participants wish to improve the the economics of NPP construction, one simple change they can make is to avoid suspending construction, insofar as they can help it.

Capacity in Megawatts: PRIS offers four measures of the rated capacity: the rated net electric capacity as originally designed, the current rating of the net electric capacity,[34] the current rating of gross electric capacity,[35] and the current rating of the thermal capacity of the reactor core. My ideal specification would select the rated thermal capacity as originally designed. Thermal capacity as is a more precise indicator of the inherent safety challenges of a larger reactor, whereas electrical capacity partly reflects not only the size but the thermodynamic efficiency of the plant. However, original thermal capacity is not available from PRIS. As a second-best, I use the original net electricity capacity, because it is a measure of the "original" size of the plant and because it lends itself to a more intuitive interpretation of the results. In any case, robustness checks revealed that none of results presented herein are sensitive to the specification of this variable.

NSSS Designer: PRIS provides the name of designer(s) of the nuclear steam supply system (NSSS). Extensive editing was performed by hand to ensure a single, consistent name for each firm. In cases where more than one firm is listed for a single reactor, the firm with more experience or

---

[34] A nuclear reactor's capacity may change over time as a result of uprates and downrates—modifications to the original design and/or changes in regulatory permissions.

[35] Gross capacity is the amount of electrical power produced by the generator. Some of that power is used to operate the reactor and power other facilities at the plant. The amount of power exported to the grid is the net capacity.

holding the intellectual property is identified as the "primary" designer.

Turbo-Generator Manufacturer: PRIS provides the name of manufacturer(s) of the steam turbine / generator set (turbo-generator). Extensive editing was performed by hand to ensure a single, consistent name for each firm. The identity of the manufacturer of the turbo-generator was ultimately not used in any of the analyses described above. Preliminary analysis found that the technical characteristics of the turbo-generator and the cumulative experience of the manufacturer were not statistically or economically significant.

Architect-Engineer: The architect-engineer (AE) is the firm which was responsible for the design of the overall plant, unifying the NSSS with the steam turbines, generator, other major infrastructure, and auxiliary buildings. This information is not provided by PRIS. Instead, I compiled the data provided by Berthélemy and Escobar Rangel [10] and Gavrilas et al. [41]. Due to the limitations of my sources, the identity of the AE firm is primarily only available for light water reactors of Western design and Canadian heavy water reactors. This data was not used in the current work due to data coverage issues but may be of use in future work.

Utility: PRIS only identifies the current owners of each reactor. Therefore, I consulted other sources to identify the original utility in the case of NPP divestments in jurisdictions that underwent liberalization of their electricity markets. From this information, I generate a categorical variable indicating whether a utility was investor-owned or state-owned at the time of construction. For utilities with mixed ownership, the categorization is based on whether private investors or governments hold a majority of shares in the company.

Reactor Type: I use the term "type" to encapsulate broad similarities in the principles of a reactor's design. The most common types are pressurized water reactors (PWR), boiling water reactors (BWR), pressurized heavy water reactors (PHWR), gas-cooled reactors (GCR), and light water graphite reactors (LWGR). All other types were aggregated into a category called "other" due to a sparsity of observations.

Reactor Family: I use the term "family" to classify reactors that have a shared evolutionary heritage. For example, all pressurized water reactors of Soviet or Russian origin are grouped into the VVER family[36] The largest family is the Westinghouse family, which includes not only PWRs designed by Westinghouse, but those designed by firms which licensed Westinghouse's intellectual

---

[36] All reactor models in this family begin with the letters VVER, which is the Russian acronym for "light water reactor."

property, notably Framatome, Siemens, and Mitsubishi. The identification of families was based explicitly on the "family trees" provided in Gavrilas et al. [41] for Western light water reactors and Sidorenko [81] for the Soviet VVER and RBMK families. The CANDU family is identified in Garland [82]; I treat India as having branched off and established a separate family of heavy water reactors after Canada (the originator of the CANDU design) cancelled its cooperation on nuclear power in response to India's first nuclear weapons test in 1974.[37] Future research could improve upon this classification scheme by properly accounting for cross-fertilization in reactor design that has occurred in recent decades.

Reactors of unconventional and experimental designs that were never iterated upon are treated as belonging to a family equal to their reactor model.

Reactor Model: I use the term the name of the model assigned by the manufacturer, where applicable. Examples of model names assigned by the manufacturer include AP-1000, CP1, P4, OPR-1000, CNP-300, VVER-213, and ABWR. For standardized reactor designs, this classification comes as close as realistically possible to identifying "identical" reactors. However, for non-standardized designs, PRIS provides an abbreviated, generalized description of the reactor's design in place of a model name. For example, "WH 4LP (DRYAMB)" indicates that the reactor is a Westinghouse design with four primary coolant loops and the containment structure operates at ambient atmospheric pressure. Information about the containment design is inconsistently included in the IAEA coding of models, so I remove it and place it in a separate varaible.

Containment Design: I classify containment as falling into one of ten categories. These are listed in Table IV. Data coverage here is imperfect, as 108 reactors are classified as having an "unknown or other" design of containment. These are primarily early and experiment reactors, but it also includes several commercial-scale BWRs that cannot be classified as either Mark I, Mark II, Mark III. Further research is needed to close these gaps in the data.

Design Characteristics: PRIS includes over 150 variables that quantify or characterize technical details of a reactor's design. Notable variables include cooling method (e.g. cooling towers vs. once-through cooling), height and diameter of the reactor pressure vessel, average density of power per unit volume of the core, reactor outlet and inlet temperature, average core power density, number of steam generators, and number of steam turbines per reactor. A handful of variables are

---

[37] This Indian family inherits the cumulative experience of the CANDU family associated with the two reactors in India for which Canada provided support.

not particularly informative, as they are necessarily implied by a reactor's type, such as choice of moderator and coolant. Unfortunately, many other variables were left blank for a large number of the observations. Most notably, safety-relevant design characteristics are sparsely provided and inconsistently coded. Presently, the only safety feature with reasonable data coverage and a clean coding is the material used for the containment structure. More work is necessary to supplement and clean the current database to enable an analysis that directly examines safety features.

Standardization: I code every reactor as either standardized (1) or non-standardized (0). A reactor was determined to be standardized if the preponderance of the literature characterized it (or all reactors of its model) as standardized. Sources consulted include Gavrilas et al. [41], Goldberg and Rosner [83], Lovering et al. [11], Csereklyei et al. [7], and back issues of *Nucleonics Week*. This dichotomous coding of standardization is not ideal, as standardization is arguably better characterized by a continuum of similarity or dissimilarity between two reactors. I generated such a continuous measure, drawing from within-model variation in design characteristics. However, in robustness checks, continuous measures of standardization were not found to contribute any meaningful explanatory power to the estimated equations above and beyond that provided by a dichotomous indicator of standardization. Therefore, I adopt the dichotomous coding as my preferred measure of standardization.

A.II. Sources and Coding of Country-Level Data

GDP per capita: I draw from the Maddison Project Database [74] for its historical estimates of GDP per capita.

Democracy: The "Polyarchy" index of electoral democracy provided by the Varieties of Democracy (V-Dem) Project [75] is my preferred measure of democracy. The V-Dem project an ongoing collaboration of "six Principal Investigators (PIs), seventeen Project Managers (PMs) with special responsibility for issue areas, more than thirty Regional Managers (RMs), 170 Country Coordinators (CCs), Research Assistants, and 3,000 Country Experts (CEs)" who generate quantitative measures of the characteristics of government. It is currently headquartered at the University of Gothenburg.

In unreported robustness checks, I also use the Polity score of democracy/autocracy from Polity IV, a project of the Center for Systemic Peace [84].

Decentralization: I test three measures of decentralization. The first is a binary indicator of whether the country has a federal or unitary constitution as of the year in which construction begins. This is a fairly coarse measure, failing to capture more complex cases like Spain. Spain formally declares itself a unitary nation, but in practice has operated with a high degree of regional autonomy ever since the end of the Franco regime and the restoration of the monarchy. Conversely, the USSR considered itself a federation of several constituent republics, but—as a totalitarian regime—operated in a highly centralized manner in practice, up until the final years in which it ultimately dissolved.

A more fine-grained metric is the "division of power index" from V-Dem. This index measures whether local and regional governments exist, whether they have elected offices, and the extent to which elected local and regional governments can "operate without interference from unelected bodies at the local [and regional] level[s]." The V-Dem codebook is careful to stress that this variable does not measure the power of local and regional governments relative to the national government. It is better conceptualized as the degree of democratic control at the local and regional levels of government. However, the primary benefit of using this measure of decentralization is that it provides complete data coverage; no observations are dropped from the analysis on account of missing data from V-Dem.

The richest measure of subnational political autonomy is from from the Regional Authority Index (RAI) by Hooghe et al. [85]. They evaluate the constitutions and political histories of individual countries and they systematically scored them on matters such as the role of subnational governments in approving constitutional change, whether the central government holds a veto over subnational decisions, and the autonomy of subnational jurisdictions in setting their tax base and rates. These scores are summed to generate indices along two dimensions of decentralization: self-rule ("the authority exercised by a regional government over those who live in the region") and shared rule ("the authority exercised by a regional government or its representatives in the country as a whole"). These two indices are then summed to generate a single, generalized measure of decentralization, which they call the Regional Authority Index (RAI). However, I only use the self-rule subindex, as it more closely pertains to the theory I elaborate in Section II.G.

To increase coverage of the RAI data, I rely on codings of self-rule from Sorens [86] for Argentina, Brazil, South Africa, and South Korea. My final dataset matches an RAI self-rule score to 452 completed reactors, out 636 total. Future replications or extensions of this research should take note that [85] report plans to expand the global coverage of the RAI database in the near future.[38]

Regime Change: I rely on data from Polity IV to identify the dates and magnitudes of regime changes. I assign a value of 1 to a reactor if it was under construction (or suspended) during an episode of major regime change, and zero otherwise. I exclude relatively minor[39] "regime transition events," such as the resignation of U.S. President Richard Nixon, which corresponds to a small increase in the Polity score for the United States of America. The resulting binary indicator largely reflects the fall of Communism in Eastern Europe. However, it also captures the Iranian Revolution and the beginning and/or ending of military dictatorships in Spain, Latin America, Asia.

Geopolitical Region: Section III.C disaggregates summary statistics by four geopolitical regions. In assigning countries to these regions, I applied the the following judgments in ambiguous cases:

Certain capitalist countries in Europe are not members of NATO (Switzerland, Sweden, and Finland) or were not members of NATO as of the year construction began (Spain prior to 1982). These nations are nonetheless classified as part of the Western Bloc due to broad similarities to NATO nations in their political, economic, and cultural characteristics, as well as their choice of Western nuclear technology.

Slovenia, while under communist rule as part of Yugoslavia during the period when the Krško NPP was built, was not classified as part of the Eastern Bloc. As a result of Tito's diplomatic "split" with Stalin and his role in the foundation of the Non-Aligned Movement, Yugoslavia imported a Westinghouse design for its reactor rather than a Soviet one. Therefore, Yugoslavia/Slovenia was assigned to the reference region.

Twenty three reactors in Eastern Bloc countries have entered commercial operation after the collapse of communist regimes (including fifteen which were under construction during episodes of regime change). Although some of these countries subsequently joined NATO, observations in

---

[38] `http://garymarks.web.unc.edu/data/regional-authority/` Accessed September 25, 2020.

[39] Specifically, I exclude all events for which the absolute value of the Polity IV variable REGTRANS is less than or equal to 1. This retains "major democratic transitions," "minor democratic transitions," "adverse regime transitions", and "state failures."

such countries are still classified as Eastern Bloc because Soviet technology was employed[40] and/or construction began prior to the collapse of communism.

East Asian countries were grouped separately from South Asian countries due to the relatively high lead times of NPPs built in India and Pakistan and relatively low lead times in East Asian nations, as compared to the global average. Because this categorization was explicitly motivated patterns in the outcome variable, it is more of a descriptive than explanatory variable. However, it should be noted that the cultural, historical, and economic differences between East Asia and South Asia are tremendous, going all the way back to their independent development as "cradles of civilization," separated by the largest mountain range on Earth.

Any country not assigned the Western Bloc, the Eastern Bloc, or East Asia was assigned to the reference category, which may be conceptualized as the Global South or the Non-Aligned Movement. Note that Argentina, Brazil, and Mexico are observers but not members of the Non-Aligned Movement.

B. METHODOLOGICAL NOTES

B.I. Exogeneity of Political Institutions

In all of the specifications described above, I take democracy and decentralization to be exogenous. Political institutions are almost surely exogenous to nuclear power plant design and construction activity. For most nations in the sample, the constitutional design was chosen long before the discovery of nuclear fission in 1938 and it has continued with only modest changes up to the present day. In the rare cases where it changed during the sample period, the lead time in constructing nuclear power plants was almost certainly unrelated to the change.[41] One may argue that the dissolution of the USSR was meaningfully hastened by the Chernobyl disaster—a theory which has been endorsed by ex-President Mikhail Gorbachev.[42] However, modeling this historical trajectory is beyond the scope of the present work. All regime changes are assumed to be exogenous for my purposes.

---

[40] With the exception of Romania, which imported a Canadian heavy water reactor design.

[41] For example, Czechoslovakia, a federal nation, dissolved and become two unitary nations on the basis of ethnic differences.

[42] Gorbachev, Mikhail. 17 April 2006. "VIEW: Turning point at Chernobyl" `https://www.gorby.ru/en/presscenter/publication/show_25057/`

In theory, countries which undergo regime change or constitutional reform should offer fertile ground for causal inference. However, too few of the observations lie on both sides of major regime changes or constitutional reforms within a single country, limiting the statistical power of a hypothetical event study. Furthermore, for NPPs which began construction under one regime and finished under another (e.g. the Soviet Union and Soviet successor states), it is hard to disentangle the effect of economic upheavals commonly associated with regime change from the effects of the new regime *per se*.

B.II. Serial Construction

149 reactors are listed as having begun construction on the same day as one or more others reactors at the same site; 132 of these are twin reactor units, along with one set of triplets, two sets of quadruplets, and one set of sextuplets. When multiple reactors are reported to have begun construction in tandem at a site, it atypical for those reactors to be completed by the same date. This reflects the fact that NPP construction management usually economizes on equipment and labor by not performing the same tasks for both reactors at the same time. Thus, the second reactor is liable to finish, approximately, one year after the first, the third one year after the second, and so on. This pattern can be almost perfectly predicted by the number assigned each to unit. For example, Calder Hall Units 1 and 2 are both listed as having begun construction on August 1st, 1953, but Unit 1 became operational four months earlier than Unit 2.

To account for this, I generate a control variable, M_i, which ranks reactors at the same site which share the same start date. The reactor with the smallest unit number (or alphabetically earliest unit letter) is assigned a value of one on M_i, the second smallest (or earliest) is assigned a value of two, and so on. A reactor which (A) has no twin or higher-order tuplet or (B) whose twin is listed as having begun construction on a different day is also assigned a value of one on M_i. Therefore, the interpretation of any coefficient on M_i refers to the marginal effect of increasing by one the number of reactors that began construction on the same date and the same site as reactor i but were prioritized over reactor i in the construction process.

B.III. Abandoned Construction and Possible Selection Bias

[Table B.I about here]

Ninety five reactors listed in PRIS began construction but have never been completed, as of September 25th, 2020, due to suspensions or cancellations. This suggests the possibility of selection bias, as reactors which are taking longer to build for reasons related to decentralization (or any other explanatory variable of interest) are more liable to have their construction abandoned due to poor economics. Table B.I summarizes these observations by country and lists known or likely explanations for the abandonment of construction. Abandoned construction can be broadly grouped into three typologies: conditions in federalist democracies (43 observations), the fall of communism and its geopolitical fallout (35 observations), and regulatory/political decisions at the national level in democracies (11 observations).

Nations transitioning out of communist regimes tended to suspend or abandon construction on their reactors for the same set of reasons: shortfalls in financing, a collapse in electricity demand, and the fresh memory of Chernobyl in the minds of voting publics. In such cases, I argue that the non-completion is attributable to regime change. In former East Germany, the newly reunited German government shut down the operating reactors and cancelled those under construction on the grounds that Soviet-designed reactors did not meet West German safety standards. The abandoned reactor in North Korea was being supplied by the United States as a condition of a 1994 agreement to incentivize North Korea to remain a party to the Non-Proliferation Treaty. Construction began in 2002 and ended a year later when the agreement broke down.

However, the slew of cancellations by utilities in the United States, primarily in the 1970s and 1980s, do present a serious selection concern. The proximate motive for these voluntary cancellations, by and large, were economic factors: budget overruns, schedule slippage, and downward revisions in electricity demand forecasts. However, the effect of the political and regulatory environment on schedule slippage is a precisely the causal mechanism under study.

The abandoned reactor in West Germany presents similar a selection concern. The SNR-300, a fast breeder reactor, began construction in 1973 near Kalkar, North Rhine-Westphalia. While its cancellation can be formally attributed to the decision in 1990 of the state government to deny permission to operate, substantial delays had already occurred due to local public protest and regulatory intervention by the state government. Had it instead been permitted to operate, it would register in the data as another observation with long lead time in a nation with high decentralization.

[Table B.II about here]

The expected selection bias due to the U.S. and West Germany is negative. In general, utilities are more likely to abandon construction on reactors that are behind schedule than those for which construction is proceeding smoothly. To the extent that the treatment (decentralization) has a causal effect on the outcome (lead time), it is expected that higher levels of the treatment cause higher rates of attrition from the study (failure to complete construction). Reactors that finish construction are in this sense a selected sample of “survivors.”

In Table B.II, I estimate two linear probability models[43] of whether suspension and completion[44] are related to the treatment variables of interest. I find that neither democracy nor decentralization are statistically meaningful predictors of either outcome, although GDP per capita is meaningfully associated with the probability that a reactor is suspended. Moreover, suspension and completion are much more strongly predicted by momentous events, namely nuclear power accidents and regime change. I take this as evidence that selection bias–insofar as it might bias downwards the coefficients on democracy and decentralization–is of minimal concern. Selection bias is almost certainly present in the coefficients on regime change and nuclear power accidents, the correction for which I discuss in Section B.IV. The regressions presented in Section V were also estimated with the Heckman correction [87], but these are not reported here because the differences in the results are quantitatively negligible.

B.IV. Modeling the Effect of Major Events

The three largest nuclear accidents—namely, those at Three Mile Island (TMI), Chernobyl, and Fukushima Daiichi—are widely recognized among industry observers as producing episodes of regulatory instability and political difficulty for nuclear power plants under construction. Finally, I also consider the effect of regime change, which is a leading cause of construction suspension and cancellation outside highly developed democracies.

---

[43] These were originally estimated with probit, but the estimated marginal effects associated with certain variables exceeded 100%; e.g. regime change was estimated to lead to 242% increase in the probability that a reactor was suspended. In the interest of credible effect sizes, the results of linear probability models are presented here. Both methods return qualitatively equivalent results in terms of which variables statistically significant and economically large.

[44] Suspension and completion are not mutually exclusive outcomes, as fourteen reactors have been suspended but were later completed.

It would be desirable to control for these events, even if they are uncorrelated with the variables of interest, for the sake of improving the precision of the model. However, there is a problem of endogenous selection into treatment (i.e. being under construction during an event). Consider two reactors that are identical on all observable characteristics and began construction on the same date.[45] If one reactor finished construction prior to the Three Mile Island accident while the the other finished after, there necessarily must exist some unobserved characteristic of the second reactor that caused it to take longer and therefore be exposed to the political/regulatory aftermath of the accident. For this reason, the estimated effect on LT is necessarily biased upwards.

To resolve this endogeneity issue, I instrument for selection into treatment with a non-linear function of the date on which construction began. To construct this instrument, I first set aside reactors which began construction after a given event. With the remaining reactors, I estimate a binary probit model that regresses selection into treatment on the date construction began. I then generate the predicted probabilities of having been still under construction as of the date of the event. For the reactors that began construction after the event, I assign a predicted probability of zero. For such reactors, the event is not an unanticipated shock.

This procedure generates the instrumental variables for selection into treatment by major events. F-statistics for the first stage of the regression reported in Column (2) of Table VII are reported on Table B.III. Nearly all of them are extremely large (greater than 50), which the exception of the instrument for being under construction during the Fukushima Daiichi disaster. The weak relevance of the instrument may be an artefact of four long-delayed reactors which began their construction prior to the year 2000, had their construction suspended for a decade or longer, and only resumed construction much later.[46] Thus, the binary probit model estimates that reactors from this era have a non-trivial probability of exposure to the Fukushima Daiichi disaster.

I argue that the exclusion criterion is satisfied for two reasons. First, the events in question are unanticipated, so they cannot have a casual relationship that flows backwards in time to influence start date. Second, the instruments have an unusual non-linear and step-wise relationship with time; they are unlikely to correlate with other possible unobserved variables that may trend over time.

---

[45] Further assume that these reactors are located at separate sites, and therefore are not being built according to a staggered schedule.

[46] The reactors are Watts Bar 2, Bushehr 1, Atucha 2, and Kalinin 4.

B.V. Measuring Cumulative Experience

The decision of how to quantify cumulative experience for the purpose of estimating learning-by-doing raises numerous issues. By convention in the literature on electricity generation technologies, the unit of measure of cumulative experience is the megawatt [3, 10]. For example, utility-scale solar and wind farms consist of so many wind turbines and solar panels that it is not particularly important to count the discrete number of panels and turbines. However, I argue that the megawatt is a less theoretically applicable unit of measure for nuclear power plant construction. Nuclear reactors are quite lumpy in nature due to their (traditionally) massive size. In my view, a firm which has built ten 200MW reactors has had five times as many opportunities for learning as a competing firm which has built a pair of 1000 MW reactors. By contrast, whether 2000 MW of solar panels are divided up into two or ten solar farms does not matter at all to the factory which produced the panels; the only difference is that there may be some modest economies of scale in the installation process for larger solar farms.

I draw on the work of Gavrilas et al. [41] and Sidorenko [81] to conclude that a credible measure of cumulative experience should (1) be global in scope, (2) recognize technological spill-overs between associated firms, and (3) account for the common evolutionary heritage of related reactor models. I argue that reactor family, as I defined it in Section III.A, best fits these criteria.

A global, rather than national, measure of cumulative experience is appropriate because most firms involved in nuclear reactor design and component supply are multinational corporations. Eight of the top ten most successful[47] families have "offspring" in more than one country; these eight families account for 85% of the observations. Experience gained by a firm in one country should, for the most part, be transferable by that firm to the business it does in another country. Furthermore, knowledge disseminates globally through organizations such as the International Atomic Energy Agency and OECD Nuclear Energy Agency.

Firms in the nuclear industry frequently license intellectual property to one another and even collaborate in reactor design, but they tend to do so within small networks that are, for the most part, stable. Reactor type is too broad of a criterion, as it would imply technological spill-overs between an American firm like Westinghouse and the Soviet Ministry of Medium Machine Building. Both built PWRs, but due to geopolitics, each firm developed its own PWR design independently.

---

[47] Where I define success as having the most completed reactors associated with a family.

Reactor model would be too narrow a criterion, because that would imply cumulative experience is entirely forfeited when a firm develops a new model. While economies in serial production of identical models almost surely enhances productivity, I am primarily interested in the learning that has occurred (if any) over the seven decades during which nuclear fission has been deployed for commercial electricity generation. Reactor models are continuously revised and replaced on comparatively shorter time-scales. For the 91 models that were built more than once, the average gap between the date on which construction on the first reactor of that model began construction and the date on which the last reactor of that model began construction was 4.5 years. By comparison, the average reactor takes longer than that to build, at a global average 7.4 years. This implies learning-by-doing has a very short time window within which to be relevant to other reactors of the same model. Instead, I argue that the benefits of learning-by-doing (if they exist) have the greatest impact on newer models within the same family.

In unreported regressions, I tested whether the effect of cumulative experience is sensitive to defining cumulative experience with a delay period between when construction begins on a reactor j and when "knowledge" is gained for the purposes of reactor i. The results were found to be robust to several possible delay periods, but the best model fit was achieved with zero delay. Therefore, I adopt zero delay as my preferred specification.

I transform the raw count of all reactors meeting the inclusion criteria (i.e. having begun construction prior to reactor i and being within the same reactor family) using inverse hyperbolic sine (IHS or $sinh^{-1}$) transformation. The inverse hyperbolic sine of a variable x is approximately equal to $ln(2x) = ln(x) + ln(2)$ for large values of x, but for small values of x it differs–chiefly in the fact $arcsinh(0) = 0$, whereas $ln(0)$ is not defined. For several of the observations, it takes on a value of 0 in the measure of cumulative experience. While a more familiar solution is to take the transformation $ln(x + 1)$, econometricians recommend IHS [88]. Bellemare and Wichman [89] provide a brief summary of how to interpret IHS coefficients. When the values of an untransformed variable is greater than 10, IHS coefficients are essentially equivalent in interpretation to the coefficients on log-transformed variables.

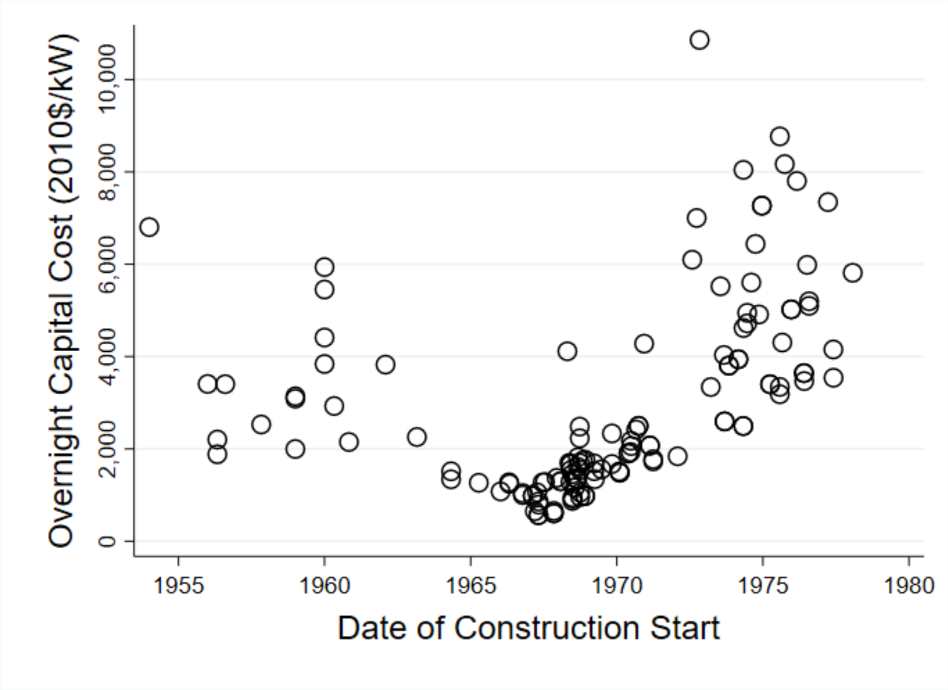

Fig. 1. Overnight Capital Costs of NPPs in the United States

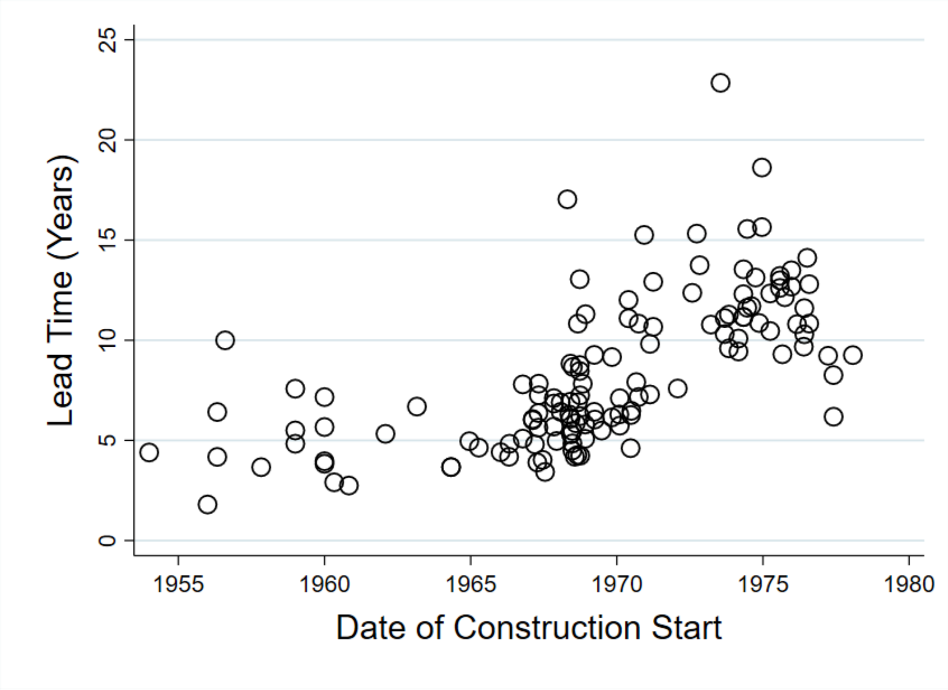

Fig. 2. Lead Time of NPPs in the United States

Western Bloc		Eastern Bloc		East Asia		Other	
United States	133	Soviet Union	69	Japan	59	India	22
France	70	Czechoslovakia	13	China	49	Pakistan	5
United Kingdom	45	Russia (post-1991)	8	South Korea	26	Argentina	3
West Germany	30	East Germany	6	Taiwan	6	Mexico	2
Canada	25	Bulgaria	6			Brazil	2
Sweden	13	Hungary	4			South Africa	2
Spain	10	Romania	2			Yugoslavia	1
Belgium	8					Iran	1
Switzerland	6						
Italy	4						
Finland	4						
Netherlands	2						
Subtotal	**350**	**Subtotal**	**108**	**Subtotal**	**140**	**Subtotal**	**38**

TABLE I
Count of Completed Reactors by Country, as September 25, 2020.

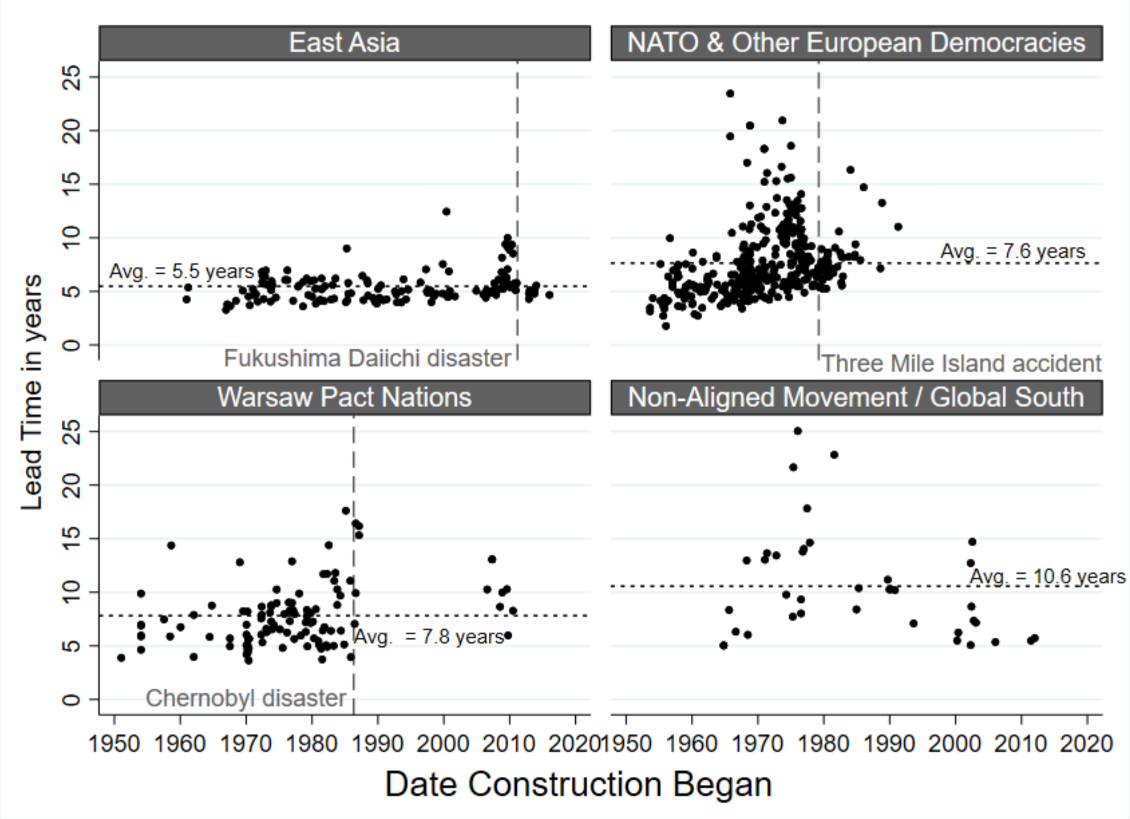

Fig. 3. Divergent Regional Trends in NPP Lead Time

Acronym	**Reactor Type**	**Mean**	**Std. Dev.**	**N**
PWR	Pressurized Water Reactor	7.4	3.2	358
BWR	Boiling Water Reactor	6.5	3.0	116
PHWR	Pressurized Heavy Water Reactor	8.2	3.4	57
GCR	Gas-Cooled Reactor	7.6	4.9	52
LWGR	Light Water Graphite Reactor	6.5	1.5	30
Other	miscellaneous reactor types	8.3	3.4	23
Total		**7.3**	**3.3**	**636**

TABLE II
Lead time (in years) by type of reactor.

Region	**Has a Federal Constitution**		**V-Dem Division of Power Index**		**RAI Self-Rule Index**	
	mean	n	mean	n	mean	n
East Asia	0.00	140	0.50	140	8.4	85
Western Bloc	0.58	350	0.87	350	16.7	350
Eastern Bloc	0.82	108	0.07	108	12.1	8
Global South	0.79	38	0.80	38	9.2	9
World	**0.5**	**636**	**0.65**	**636**	**14.9**	**452**

TABLE III
Descriptive Statistics of Decentralization by Global Region

Dependent Variable: $ln(LT_i)$

	Marginal Effect	(Standard Error)
100 MWe increase in power output	**6.0%**	(0.8%)
1°C increase in temperature rise across the reactor core	**0.22%**	(0.06%)
1 MPa increase in operating pressure of the primary coolant	**-1.2%**	(1.1%)
One additional primary coolant loop	**3.1%**	(2.1%)
One additional pump/circulator in the reactor coolant system	**-0.7%**	(0.9%)
Standardized reactor design	**-16.8%**	(4.0%)
Plutonium co-production	**-65.9%**	(10.4%)
Once-through cooling to discharge waste heat	**-11.5%**	(3.8%)
Measurement error related to multi-unit construction	**10.0%**	(2.1%)
Reactor Type Fixed Effects		
PWR: pressurized water reactor *(reference category)*	—	(N/A)
BWR: boiling water reactor	**-32.1%**	(9.6%)
PHWR: pressurized heavy water reactor	**-11.4%**	(10.3%)
GCR: gas-cooled reactor	**96.3%**	(72.1%)
LWGR: light water graphite reactor	**-15.2%**	(24.2%)
Other: miscellaneous reactor designs	**-25.5%**	(16.9%)
Containment Design Fixed Effects		
Large Dry *(reference category)*	—	(N/A)
Subatmospheric	**-10.5%**	(11.7%)
Vacuum Building	**7.1%**	(12.3%)
Ice Condenser	**9.6%**	(12.1%)
Concrete Pressure Vessel	**-46.3%**	(13.7%)
Mark I	**27.5%**	(17.5%)
Mark II	**28.5%**	(18.3%)
Mark III	**35.5%**	(20.7%)
No Containment	**9.3%**	(29.7%)
Other Containment / Missing Data	**44.6%**	(17.1%)
Country Fixed Effects	✓	
Year Fixed Effects	✓	
Observations	538	

TABLE IV
Marginal Effects of Select Design Characteristics on NPP Lead Time

Dependent Variable: 1 if the reactor is standardized, 0 otherwise

	(1)	(2)	(3)	(4)
GDP per capita	**2.11**	**1.94**	**23.7**	**1253.7**
one S.D. increase in $ln(GDPpc_{c,y})$	(1.55)	(1.22)	(1.85)	(2.45)
Democracy	**0.80**	**2.03**	**2.55**	**1.09**
one S.D. increase in Dem	(-0.69)	(1.32)	(1.26)	(0.13)
Decentralization	**0.92**			
1 if country has a federal constitution	(-0.12)			
one S.D. increase in $Dec_{c,y}$ (V-Dem)		**0.35**		
		(-1.93)		
one S.D. increase in $Dec_{c,y}$ (RAI)			**0.34**	**0.52**
			(-2.60)	(-1.48)
Population				**1.92**
$ln(Pop_{c,y})$				(1.62)
Electricity Sector Fragmentation				**0.20**
$ln(NumUtil_c)$				(-2.92)
Investor-Owned Utility	**0.20**	**0.29**	**0.34**	**1.36**
IOU_i	(-2.55)	(-1.96)	(-1.64)	(0.49)
Time Trend	**1.14**	**1.14**	**1.15**	**1.07**
year construction began	(3.65)	(3.52)	(2.55)	(0.80)
N	754	754	514	514

Odds ratio in **bold.** (t-statistics in parentheses.)

TABLE V
Predictors of Reactor Design Standardization

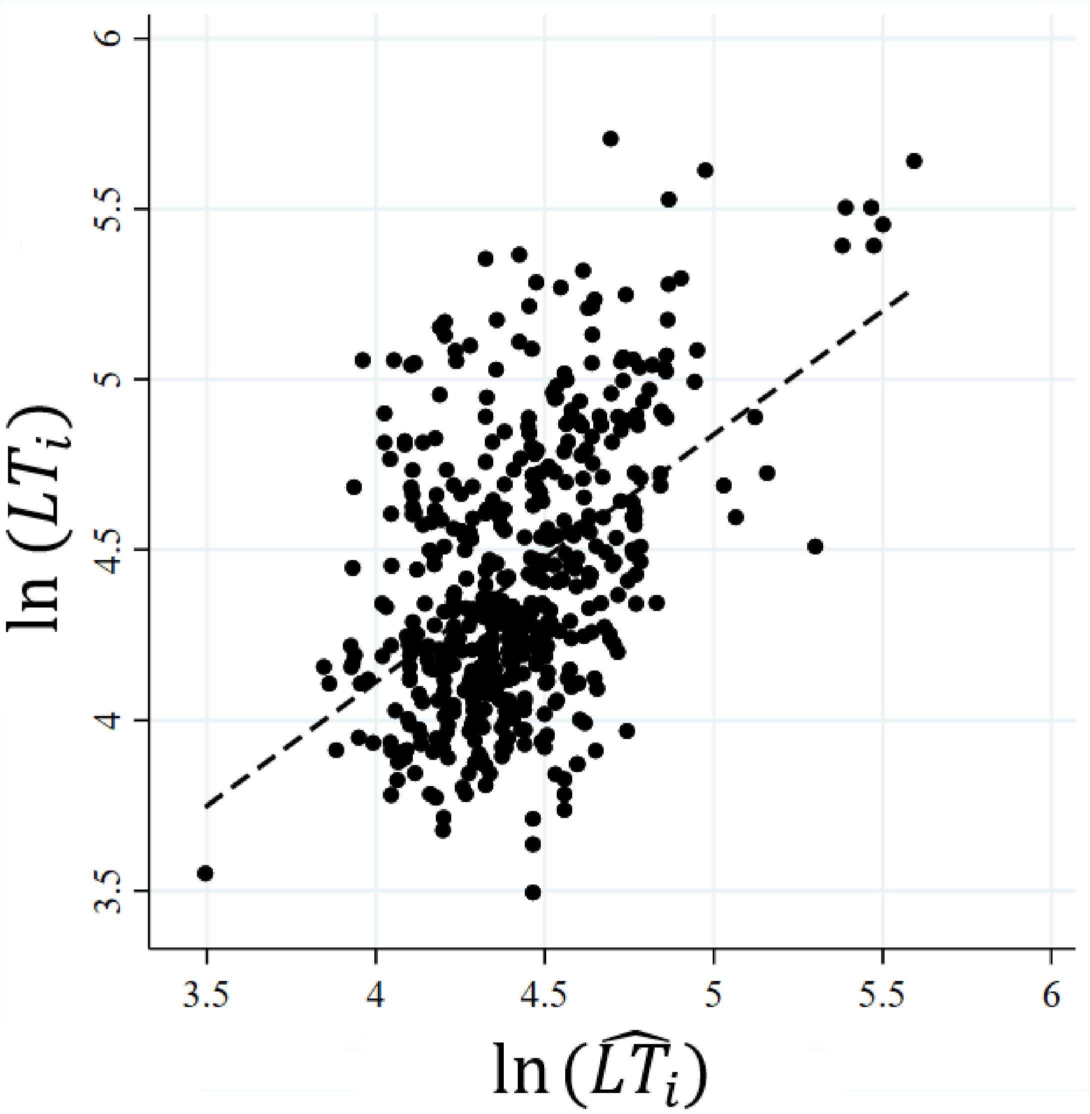

Fig. 4. Goodness of Fit of Equation 3

Dependent Variable: $ln(\widehat{LT_i})$

	(1)	(2)	(3)	(4)
GDP per capita	**15.4%**	**14.4%**	**11.2%**	**2.0%**
one S.D. increase in $ln(GDPpc_{c,y})$	(3.12)	(3.35)	(0.86)	(0.37)
Democracy	**2.9%**	**5.4%**	**3.5%**	**4.1%**
one S.D. increase in $Dem_{c,y}$	(1.27)	(1.17)	(0.65)	(0.69)
Decentralization	**-5.2%**			
1 if country has a federal constitution	(-0.90)			
one S.D. increase in $Dec_{c,y}$ (V-Dem)		**-2.1%**		**0.5%**
		(-0.58)		(0.12)
one S.D. increase in $Dec_{c,y}$ (RAI)			**0.6%**	
			(0.13)	
Capacity				**3.9%**
100 MWe increase in power output				(3.26)
Observations	520	520	364	520
adjusted R^2	0.145	0.138	0.029	0.319

Transformed marginal effects on $\widehat{LT_i}$ in **bold.** (t-statistics in parentheses.)

TABLE VI
Estimation Results of Equation 4

Dependent Variable: $ln(LT_i)$

	(1)	(2)	(3)
Three Mile Island Accident	**19.9%**	**18.9%**	**30.7%**
under construction on 3/28/1979	(3.68)	(3.09)	(2.91)
Three Mile Island Accident × USA	**43.0%**	**54.4%**	**32.0%**
under construction on 3/28/1979 in the USA	(4.95)	(5.45)	(3.11)
Chernobyl Disaster	**4.19%**	**3.48%**	**1.40%**
under construction on 4/26/1986	(0.62)	(0.53)	(0.16)
Chernobyl Disaster × USSR	**-30.4%**	**-27.4%**	*not*
under construction on 4/26/1986 in the USSR	(-2.24)	(-2.44)	*estimable*
Fukushima Daiichi Disaster	**-0.30%**	**-8.73%**	**-7.65%**
under construction on 3/11/2011	(-0.03)	(-0.53)	(-0.23)
Regime Change	**51.5%**	**50.7%**	**4.34%**
under construction during regime change	(3.25)	(3.18)	(0.21)
GDP per capita	**-9.02%**	**-1.60%**	**-0.39%**
one S.D. increase in $ln(GDPpc_{c,y})$	(-1.66)	(-0.19)	(-0.031)
Democracy	**-2.15%**	**-10.7%**	**-14.8%**
one S.D. increase in $Dem_{c,y}$	(-0.56)	(-1.86)	(-3.23)
Decentralization	**22.0%**		
1 if country has a federal constitution	(3.36)		
one S.D. increase in $Dec_{c,y}$ (V-Dem)		**9.74%**	
		(1.78)	
one S.D. increase in $Dec_{c,y}$ (RAI)			**8.96%**
			(2.96)
Investor-Owned Utility	**-14.5%**	**-14.1%**	**-14.6%**
IOU_i	(-4.13)	(-2.94)	(-4.86)
Expected LT, conditional on design	**0.39%**	**0.41%**	**0.33%**
one percent increase in $\widehat{LT_i}$	(1.66)	(1.59)	(1.28)
Reactor Model Fixed Effects	✓	✓	✓
Observations	484	484	346
adjusted R^2	0.485	0.459	0.516

Transformed marginal effects on LT_i in **bold.** (t-statistics in parentheses.)

TABLE VII
Estimation Results of Equation 5

Dependent Variable: $ln(LT_i)$

	(1)	(2)	(3)	(4)	(5)
Expected LT, conditional on design	**0.91%**	**0.93%**	**0.87%**	**0.86%**	
one percent increase in $\widehat{LT}_i$	(15.9)	(14.2)	(15.5)	(10.9)	
Expected LT × Democracy		**-0.000%**	**-0.025%**	**-0.017%**	
... × one S.D. increase in $Dem_{c,y}$		(-0.00)	(-1.70)	(-1.22)	
Expected LT × Decentralization		**-0.049%**			
... × 1 if country has a federal constitution		(-0.43)			
... × one S.D. increase in $Dem_{c,y}$ (V-Dem)			**0.051%** (3.41)		
... × one S.D. increase in $Dem_{c,y}$ (RAI)				**0.036%** (3.88)	
Expected LT × East Asia					**0.60%**
one percent increase in $\widehat{LT}_i$ *in East Asia*					(5.50)
Expected LT × Western Bloc					**0.98%**
one percent increase in $\widehat{LT}_i$ *in the Western Bloc*					(13.80)
Expected LT × Eastern Bloc					**0.88%**
one percent increase in $\widehat{LT}_i$ *in the Eastern Bloc*					(3.33)
Expected LT × Global South					**1.33%**
one percent increase in $\widehat{LT}_i$ *in the Global South*					(2.34)
GDP per capita	**-3.28%**	**-3.00%**	**-12.2%**	**-4.76%**	**-3.65%**
one S.D. increase in $ln(GDPpc_{c,y})$	(-0.24)	(-0.20)	(-0.95)	(-0.22)	(-0.28)
Investor-Owned Utility	**-9.92%**	**-10.2%**	**-9.86%**	**-8.56%**	**-9.51%**
IOU_i	(-1.69)	(-1.69)	(-1.69)	(-1.38)	(-1.63)
Reactor Family Fixed Effects	✓	✓	✓	✓	✓
Country Fixed Effects	✓	✓	✓	✓	✓
Year Fixed Effects	✓	✓	✓	✓	✓
Nuclear Accidents & Regime Change	✓	✓	✓	✓	✓
Observations	489	489	489	345	489
adj. R^2	0.445	0.443	0.465	0.444	0.453

Transformed marginal effects on LT_i in **bold.** (t-statistics in parentheses.)

TABLE VIII
Estimation Results of Equation 6

Dependent Variable: $ln(LT_i)$

	(1)	(2)	(3)	(4)	(5)	(6)
Cumulative Experience	**0.004**	**-0.018**	**-0.016**	**-0.084**	**-0.115**	**-0.142**
$sinh^{-1}(Exp_{i,f})$	(0.13)	(-0.64)	(-0.45)	(-4.34)	(-5.62)	(-7.12)
Cum. Exp. × Democracy	**0.018**	**-0.013**	**-0.007**	**0.028**	**0.012**	**0.022**
... × one S.D. increase in $Dem_{c,y}$	(1.76)	(-0.89)	(-0.54)	(3.05)	(0.83)	(1.67)
Cum. Exp. × Decentralization	**-0.016**			**-0.041**		
... × 1 if country has a federal constitution	(-0.45)			(-1.57)		
... × one S.D. increase in $Dec_{c,y}$ (V-Dem)		**0.036**			**0.018**	
		(2.89)			(1.41)	
... × one S.D. increase in $Dec_{c,y}$ (RAI)			**0.029**			**0.022**
			(2.84)			(1.88)
Reactor Family Fixed Effects	✓	✓	✓			
Start Year Fixed Effects				✓	✓	✓
Country Fixed Effects	✓	✓	✓	✓	✓	✓
Additional Controls per Eqs. 7 and 8	✓	✓	✓	✓	✓	✓
Observations	589	589	422	595	595	427
Adjusted R^2	0.570	0.589	0.640	0.284	0.274	0.239

Untransformed regression coefficients in **bold.** (t-statistics in parentheses.)

TABLE IX
Learning Parameters Estimated per Equations 7 and 8

Country	**Count**	**Known or Likely Reasons**
Austria	1	national referendum banning nuclear power
Brazil	1	corruption scandal
Bulgaria	2	fall of communist regime
Cuba	2	termination of Soviet aid
Czechoslovakia	2	fall of communist regime
East Germany	5	German re-unification
Iran	1	suspended during Islamic Revolution, damaged during Iran-Iraq War
Italy	3	national referendum banning nuclear power
Japan	2	in limbo due to post-Fukushima regulatory environment
North Korea	1	breakdown of diplomatic agreement
Philippines	1	national executive decision
Poland	2	fall of communist regime
Romania	3	fall of communist regime
Spain	4	national legislative decision
Soviet Union	4	short-term response to Chernobyl accident (RBMK design or other safety issues)
	14	fall of communist regime
	1	suspended after Chernobyl, later restarted, canceled after Fukushima
Taiwan	2	national executive decision
United States	42	cancellation by utility
West Germany	1	permission to operate denied by state government
World	**95**	

TABLE B.I
Reactors for which Construction was Abandoned or is Presently Suspended

Dependent Variable (1): 1 if ever suspended, 0 otherwise
Dependent Variable (2): 1 if ever completed, 0 otherwise

	(1)	(2)
GDP per capita	**5.5%**	**-2.7%**
one S.D. increase in $ln(GDPpc_{c,y})$	(2.39)	(-1.06)
Democracy	**-0.3%**	**-1.3%**
one S.D. increase in $Dem_{c,y}$	(-0.09)	(-0.41)
Decentralization	**1.0%**	**-0.06%**
one S.D. increase in $Dec_{c,y}$ (V-Dem)	(0.35)	(-0.02)
Investor-Owned Utility	**-10.5%**	**7.3%**
IOU_i	(-2.61)	(1.74)
Three Mile Island Accident	**-5.9%**	**2.9%**
under construction on 3/28/1979	(-1.79)	(0.93)
Three Mile Island Accident × USA	**53.9%**	**-47.9%**
under construction on 3/28/1979 in the USA	(6.75)	(-5.74)
Chernobyl Disaster	**9.0%**	**-8.5%**
under construction on 4/26/1986	(1.14)	(-1.08)
Chernobyl Disaster × USSR	**25.2%**	**-20.3%**
under construction on 4/26/1986 in the USSR	(1.67)	(-1.19)
Fukushima Daiichi Disaster	**6.1%**	**-6.9%**
under construction on 3/11/2011	(1.09)	(-1.32)
Regime Change	**75.8%**	**-54.8%**
under construction during regime change	(4.70)	(-3.69)
Observations	754	720

Marginal effects on the probability of the outcome in **bold.** (t-statistics in parentheses.)
Reactors presently under construction are excluded from column (2).

TABLE B.II
Predictors of Construction Suspension and Completion

	First Stage F-Statistic
Three Mile Island Accident *under construction on 3/28/1979*	263
Three Mile Island Accident × USA *under construction on 3/28/1979 in the USA*	2251
Chernobyl Disaster *under construction on 4/26/1986*	82
Chernobyl Disaster × USSR *under construction on 4/26/1986 in the USSR*	386
Fukushima Daiichi Disaster *under construction on 3/11/2011*	7.24
Regime Change *under construction during regime change*	58
Observations	484

TABLE B.III
Relevance of Instruments for Column (2) of Table VII

Abbreviation	Full Description
LT_i	Lead time of the reactor in months, net of any months of suspended construction
$\widehat{LT_i}$	Predicted value of LT_i, conditional on design characteristics (see Section IV.A)
$Dem_{c,y}$	index of democracy in country c as of year y
$Dec_{c,y}$	index of decentralization in country c as of year y
$GDP_{c,y}$	GDP per capita in country c as of year y, in 2011USD
$Spec_{s,i}$	any of S design characteristics and specification variables for reactor i
MW_i	net electric capacity (original design rating) of reactor i
OTC_i	takes on the value 1 if reactor i uses once-through cooling, and 0 otherwise
Pu_i	takes on the value 1 if reactor i co-generates plutonium for weapons, and 0 otherwise
IOU_i	takes on the value 1 if reactor i was ordered by an investor-owned utility, and 0 otherwise
$NumUtil_c$	number of utilities appearing in the dataset for country c
M_i	a control for measurement error related to multi-unit construction (see Appendix B.II)
δ_t	fixed effect for reactor type t
δ_f	fixed effect for reactor family f
δ_m	fixed effect for reactor model m
μ_c	fixed effect for country c (as of the year reactor i began construction)
ν_y	fixed effect for year y (year in which reactor i began construction)
ξ_y	any of several indicator variables that takes on the value 1 if reactor i was under construction during event x, and 0 otherwise (see Appendix B.IV)
ε_i	error term

TABLE B.IV
Abbreviations and Symbols used in the Econometric Specifications