Unbundling the Atom:

Nuclear Power Plant Reliability in the Neoliberal Era

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Abstract

The operational reliability of nuclear power plants (NPPs) has globally trended upwards over time since the 1970s. Davis and Wolfram (2012) show that the transfer of NPP ownership from vertically-integrated utilities under cost-of-service regulation to independent power producers operating in competitive wholesale electricity markets partially explains this trend in the United States. However, international data reveal persistent and large cross-country differences in NPP reliability. Notably, NPPs in the United States substantially outperform their peers in other highly developed economies, even those with earlier and more comprehensive liberalizations of their electricity sector. The present work extends the analysis of Davis and Wolfram (2012) to the global population of NPPs to encompass a diverse set of market structures and regulatory frameworks under which countries restructured their electricity markets beginning in the 1990's. I find the effects of restructuring on NPP reliability vary widely by country, with the clearest successes in the United States and Canada.

Keywords: nuclear power, reliability, deregulation, restructuring, competition, electricity markets

JEL Codes: L11, L51, L94, L98, Q42, Q48

1 Introduction

Owners of capital equipment with low marginal operating cost should generally seek to maximize its utilization, provided that utilization avoids a higher marginal cost or profitably serves demand that would otherwise go unmet. It is on the basis of this principle that investment in expensive capital equipment is justified. However, in the absence of discipline by market forces, firms may neglect to utilize their capital equipment efficiently. Such neglect may arise, for example, in a monopoly firm subject to rate-of-return regulation, whereby the profit they earn is the rental rate of "prudently invested" capital, rather than a function of the efficiency of current operations.

The global wave of restructuring, liberalization, and deregulation of industries formerly thought to be natural monopolies (or otherwise in need of economic regulation) has given new emphasis to the aforementioned principle. For example, deregulation has set the stage for substantial improvements in capacity utilization in the American trucking (Hubbard, 2003) and airline (Dana and Orlov, 2014) industries. In the context of the electricity sector, Davis and Wolfram (2012) find dramatic improvements in the capacity utilization of US nuclear power plants that were divested and operated in competitive wholesale markets, as compared against those which remained vertically integrated under the ownership of either regulated, privately-owned utilities or government-owned utilities.[1]

I extend the work of Davis and Wolfram (2012) to a nearly complete global sample of nuclear power plants. This provides an empirical setting with more variation in the timing of the treatment and a broader array of liberalized market structures. I find that liberalization in the United States and Canada is associated with large improvements in reliability for nuclear power plants, but modest or no improvements elsewhere in the world.

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[1] American readers may be more familiar with the terms "investor owned utility" (IOU) and "publicly-owned utility" (POU). I avoid these terms due to potential confusion with "public utility" (which refers the utility's function in providing a public service) and "publicly traded" utility (privately-owned utilities may or may not be publicly traded).

2 Prior Literature and Theory

2.1 Electricity Sector Restructuring

Prior literature has found evidence predominantly in favor of the view that restructuring and liberalization enhances the efficiency of the electricity sector. Privately-owned power plants operating in restructured U.S. markets reduced operating expenses (Fabrizio et al., 2007) and emissions (Chan et al., 2017) more than privately-owned power plants in regulated markets. U.S. coal plants divested from ownership by regulated utilities exhibit reductions in prices paid for fuel through more efficient procurement strategies and a lower propensity to adopt capital-intensive pollution abatement technology (Cicala, 2015). However, issues such as market power (Mansur, 2008) and the distribution of surplus and rents (Borenstein and Bushnell, 2015) cause the merits of restructured electricity markets to continue to be contested.

The literature has been largely focused on the United States, in part because of the natural quasi-experiment arising from (A) the differential timing of restructuring on a state-by-state basis, (B) the absence of restructuring in some states, and (C) the presence of government-owned utilities, which form an additional control group. The literature on non-U.S. settings returns qualitatively similar findings. Indian states which unbundled their publicly-owned, vertically-integrated utilities by transferring management of their power plants to autonomous, corporatized (but still state-owned) generating companies benefited from a 25% reduction in forced outages and 10% increase in availability at their coal-fired plants (Malik et al., 2015). The restructuring and privatization of Britain's Central Electricity Generating Board (CEGB) resulted in an estimated 5% reduction in costs, including through improvements in operating efficiency of generators, fuel switching away from uneconomic domestic coal, and less capital-intensive investments in new generating capacity (Newbery and Pollitt, 1997). However, due to the initial divestiture of generating assets to too few firms, the exercise of market power meant that most of those gains accrued to firms, although this was later remedied (Newbery, 2006). In Turkey, during the privatization process from 2009 to 2013, wholesale power prices declined by 10% while retail rates increased by 5.8%, leading to public dissatisfaction with the results (Karahan and Toptas, 2013).

For a comprehensive review of the successes, failures, institutional details, and ongoing issues in restructured electricity markets, the reader is directed to Joskow (2008), who draws on both U.S. and international experience. Suffice it to say that "electricity sector restructuring" entails different policies and different market structures in different countries. Below, I outline a broad typology of reforms that specifically relate to electricity generation and elaborate their theorized impact on nuclear power plant reliability.

A typical first reform in the restructuring process is unbundling, the formal separation of entities involved for generation from those involved in other segments of the electricity supply chain. This type of reform is motivated by the theory of soft and hard budget constraints (Kornai, 1986). An organizational unit purely engaged in generation is thought to be subject to greater transparency and accountability about its production, output, revenue and costs. This should make it easier for regulators or owners to oblige that entity to cover its costs with revenues from generation, rather than relying on state aid or cross-subsidization from other parts of the business.

Privatization is conceptually distinct from unbundling. Vertically-integrated utilities can be privately-owned; state-owned utilities can be unbundled without a change in ownership. Privatization is theorized to increase efficiency of firm operations as a consequence of the profit motive. However, if a privately-owned firm remains a regulated monopoly, it may not be the residual claimant to increased output or decreased costs, which dulls the incentive to firm managers to identify and implement opportunities for efficiency improvements.

Unbundling may or may not be economically meaningful if the the unbundled generation entity is still owned, in whole or in part, by an entity that also owns transmission distribution assets. For example, Korea Electric Power Corporation (KEPCO) was formerly the vertically-integrated, state-owned, national electric utility of South Korea. In 2001, its generation and assets were unbundled into several companies in preparation for further liberalization of the electricity market. However liberalization stalled; Korea Hydro & Nuclear Power (KHNP), which owns and operates South Korea's hydroelectric and nuclear power plants; today remains a wholly owned subsidiary of KEPCO.[2] This sort of unbundling is termed "legal unbundling." Without vigilant regulation or the discipline of market forces, legally unbundled entities may still behave as a vertically integrated firm by, for example, coordinating to use its control of the transmission system to provide favorable dispatch of a corporate affiliate's generation at the expense of competitors' generation.

The creation of wholesale electricity markets relieves regulators of the need to closely monitor the costs and output of power plants to determine whether firms are managing and maintaining them optimally. The first fundamental theorem of welfare economics predicts that the invisible hand of the market will guide self-interested, price-taking firms to the optimal allocation of resources. However, the techno-economic features of electricity generation allow for substantial departures from the theoretical ideal of perfect competition. Inelastic demand and capacity constraints (both in generation and transmission) can enable anti-competitive behavior. Anti-competitive behavior in wholesale electricity markets is well-documented (Wolfram, 1999), even at seemingly low levels of market concentration (Borenstein, 2002). Further, in the absence of reforms to retail pricing of electricity, electricity demand tends to be extremely inelastic, which increases the scope for monopolistic pricing.

2.2 Nuclear Power Plant Operational Performance

The earliest literature on the operational performance of NPPs exhibits considerable debate over the nature and causes of low capacity factors, averaging 62.3% globally in the 1970s.[3] An article in the *Bulletin of the Atomic Scientists* rhetorically asked, "Will Idle Capacity Kill Nuclear Power?" (Comey, 1974). Considerable debate was waged over the interpretation of

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[2] `http://cms.khnp.co.kr/eng/content/478/main.do?mnCd=EN01040102` Accessed June 11, 2019.

[3] Author's own calculations from PRIS.

the scarce data available at the time (Margen and Lindhe, 1975; Komanoff, 1976; Joskow and Rozanski, 1977), but we now know—with the benefit of fifty years of hindsight—that the earliest decades of the industry were not representative of future performance. The capacity factor of nuclear power plants today vastly exceeds that of any other generating technology in nearly every country in which they operate.

The high capacity factor of nuclear power plants is partly a consequence to the merit-order effect—the lower a plant's marginal cost of generation, the greater the priority with which it is dispatched to meet demand. Therefore, a high capacity factor is a strong indicator of an efficiently-operating nuclear power plant. However, the logic of the merit order cannot explain changes in capacity factor over time because nuclear's ranking within the merit order has never changed, even as the relative prices of uranium, coal, and natural gas have fluctuated over the decades. Rather, the capacity factors we observe today–in excess of 90% and approaching the theoretical maximum of 100%—were made possible by dramatic improvements in reliability. These include: n

> olistsep]**Shorter refueling outages.** Most (but not all) designs of nuclear power plants require the plant to not operate when replacing spent fuel with fresh fuel. In the United States, the duration of refueling outages has fall from a high of 80 days in 1997 to 33 days in 2017.[4] **Fewer unplanned outages.** An unplanned outage is a period of non-operation typically caused by the malfunction or deterioration of a plant component or system. Improved maintenance and learning-over-time about best practices can result in fewer unplanned outages. **Regulatory Environment.** In earlier decades, when nuclear power was still relatively technologically immature and regulations were being developed and revised to address newly discovered safety issues, regulatory decisions were a relatively more common cause of non-operation as compared to today.

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[4] U.S. Energy Information Agency. "U.S. nuclear plant outages increased in September after remaining low during summer." Published 15 October 2018. `https://www.eia.gov/todayinenergy/detail.php?id=37252`Accessed 20 September 2019.

A learning-by-doing effect in the operations of nuclear power plants (NPPs) was first postulated and tested by Joskow and Rozanski (1977). With the benefit of more years of data to look back on, Lester and McCabe (1993) compare France and the United States in their learning about NPP operational performance. Their analysis attributes France's higher reliability (at that time) to France's greater standardization in reactor design and the industrial organization of the French electricity sector (as a single national monopoly), facilitating transfers of lessons learned across NPP sites. However, circumstances have since reversed the comparison. From 2009 to 2018, availability factors of NPPs averaged 92% in the United States and 73% in France.

2.3 Nuclear Power Plants in Restructured Electricity Markets

The seminal work on the performance of NPPs in restructured electricity markets is Davis and Wolfram (2012). Using monthly panel data of US nuclear power plants from 1970 to 2009 and daily panel data from 1999 to 2009, they estimate a 10% increase in output by divested NPPs relative to non-divested NPPs. This is largely attributable to greater uptime—particularly shorter outages—but also to a greater magnitude of uprates.[5] Their back-of-the-envelope calculations estimate that this improvement in output corresponds to additional revenue of approximately \$2.5 billion (2012 dollars), of which approximately 14% is offset by increased operating costs and capital additions. Additionally, they estimate that the attendant displacement of fossil fuels reduces carbon dioxide emissions by about 35 million tons per year.

Given the large private and external benefits associated with improvements in NPP output, it is worth asking why large cross-country disparities in NPP operational reliability persist. The primary hypothesis I study is the possibility that unique features of electricity sector restructuring in the United States explains a substantial part of the difference. I posit that reforms which make NPP owners the residual claimant on increased revenue and

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[5] Uprates are changes to equipment and operations, authorized by safety regulators, that enable a higher capacity rating, i.e. greater power output.

avoided costs will have the strongest positive effect on operational performance.

3 National and Subnational Histories of Electricity Sector Restructuring

To construct the treatment variables, I reviewed a variety of sources to ascertain the ownership, regulatory, and market structure of electricity sector for each of the 38 countries which appear in the sample. This research also included the same for U.S. states and Canadian provinces with nuclear power plants. Special attention was paid to the status of nuclear power plants, as their original arrangements and ultimate fate frequently differ from those of other types of generation. Sources reviewed include academic literature, reports of international intergovernmental bodies (IAEA, IEA, OECD), industry news articles, and the websites of the relevant governments and utilities. Below, I discuss the methodology by which I encoded qualitative narratives of electricity sector restructuring into categorical variables with specific dates indicating when a reform becomes operational. A file providing the variable coding, dates of reform, sources cited, and discussion for every individual country and reactor is available as a data appendix to this paper. Here, I provide a discussion of key trends and patterns that emerge from these data that will be relevant to the analysis.

3.1 Encoding of Restructuring Variables

For each reactor, I encode three variables representing the following aspects of the electricity sector: (1) vertical integration, (2) public or private ownership, and (3) wholesale markets.

The variable for vertical integration can take on one of four possible values. A reactor is coded as bundled if it is owned and operated by an entity that is also directly involved in any regulated activity. Regulated activities include transmission and distribution in all cases; this may also include retail energy supply in cases where it is still regulated and bundled with generation. A reactor is coded as legally unbundled if it is owned by an entity that is also involved in any regulated activity but management of regulated activities and competitive activities is kept at arms-length through strict legal separation. This is typically achieved by converting the formerly vertically integrated utility into a holding company of several legally distinct subsidiaries. In the European Union, where this arrangement is most prevalent, subsidiaries operating in the regulated sectors (transmission and distribution) are subject to strict regulatory requirements to ensure non-discriminatory access to the grid and forbidding unfair sharing of information with affiliates in the competitive sectors.

A reactor is coded as ownership unbundled if it is owned by an entity that is not involved in any regulated activity in the jurisdiction where the reactor operates. This definition allows for the possibility that a firm might own regulated assets in another jurisdiction but effectively operate as an fully divested independent power producer in the jurisdiction of the reactor of interest. An example of this includes Électricité de France (EDF), which purchased several British nuclear power plants in 2009. EDF operates in a competitive British wholesale and retail markets but has no interest in British transmission or distribution assets; meanwhile, EDF's reactors in France supply energy at regulated, cost-of-service rates to French households and small businesses.

A final possible coding for the vertical integration is leased. This only characterizes the eight reactors at Bruce Nuclear Generating Station in Ontario Canada. Further description of this arrangement is provided in section 3.2 All of the firms that own Bruce Power share the characteristics of ownership unbundled firms in the sense that they do not also own regulated assets in Onatrio's electricity sector. Except where specified, leased is treated as identical to ownership unbundled because of the limited statistical power of using these 8 reactors, all of which are jointly managed at a single firm at a single site, to estimate the effect of leasing separately from any other arrangement.

The variable for public or private ownership of a reactor is binary in nature, taking on the values majority public and majority private. In case of an exact 50/50 split, ties are broken by the ownership type of whichever company is the listed as the operator in IAEA PRIS. If the operator is a third company specifically dedicated to operating the plant which is itself owned in an exact 50/50 public/private split, this variable takes the value "private."[6]

The crude nature of this coding was a result of several limitations and difficulties in the sources available. Many utilities and reactor holding companies experienced several changes in the exact distribution of ownership shares over a period of decades; few sources were found that reliably recorded this for reactors with a complex ownership histories. The challenge proliferates when a plant has several owners, one or more of which may be partially state-owned. The data that were most frequently available in the historical sources were the dates of large-scale privatizations, particularly those when the plant's ownership switched from majority public to majority private.

Therefore, I chose to limit the analysis to this binary measure, as it could be most reliably established for all plants in the sample. This can be partly justified by the following theoretical prediction: in cases where private and public interests in the management of a company conflict, the preferences of the majority of shareholders will prevail. However, there are good reasons to expect that the degree of public ownership matters, even when it is inframarginal to the issue of a majority shareholding. For example, several historical sources in Germany make reference to the power of *länder* to appoint directors to the boards of utilities in which the *land* is a minority shareholder. Conversely, one might hypothesize that privatization of a minority stake in a utility exposes it to some accountability and fiscal discipline that is not felt by a non-for-profit utility that functions as a department of a municipality, region or national government. Gathering historical data on the precise share of state ownership of nuclear power plants is an opportunity for further research outside of the scope of the present work.

The variable for wholesale markets may take on one of two possible values: competitive if the reactor operates in a jurisdiction where generation has open access to the transmission system and dispatch is decided by competitive markets managed by an independent entity,

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[6] This final tie-breaking procedure was employed in a single case: Santa maría de Garoña, a single BWR in Spain.

or uncompetitive. Negotiated third-party access to the transmission system and the ability to conduct bilateral trades are insufficient to be categorized as competitive by this scheme. In instances where various product markets are introduced at different times (e.g. real-time balancing, day-ahead energy markets, capacity markets, ancillary services), I take the first date of operation of day-ahead energy markets as the date on which this variable switches from uncompetitive to competitive.

The data for the outcome of interest (reliability) is recorded on a monthly basis. Thus, if a restructuring variable changes its status on a date other than the first of the month, there is some ambiguity as to how to accurately encode the variable. If the effective date of the reform is prior to the 15th day of the month, I encode the reform as having changed the variable to a new coding in that month. If the effective date of the reform is on or after the 15th day of the month, I encode the reform as having changed the variable to a new coding in the following month.

3.2 Discussion of Key Trends and Patterns

The coding of every reactor on each of these variables is available in the data appendix, along with sources cite and notes explaining any potentially ambiguous codings. This section will provide an overview of key trends and patterns that emerge from the data that will be relevant for the analysis.

Few countries exhibit subnational variation in the original or restructured industrial organization of their nuclear power plants. The primary exceptions to this pattern are found in the Anglophone countries: the United States, Canada, and the United Kingdom. In North America, subnational variation arises due to the federalism. The history of this is sufficiently covered for the United States by Davis and Wolfram (2012). In Canada, several unique developments in the electricity sector are worth mentioning. The province of Ontario, which is home to all but 3 of Canada's nuclear reactors, unbundled but did not privatize Ontario Hydro in April of 1999. In May 2001, Ontario Power Generation (the unbundled operator of

Ontario's NPPs) leased one of its three plants—accounting for 8 of its 20 reactors—to Bruce Power (a partnership of several privately-owned corporations, labor unions, and a provincial pension fund). Bruce Power receives a long-term, contracted price per MWh generated. It has borne the expense of several costly refurbishments to bring mothballed units back into service and by all accounts is the residual claimant on increased output and decreased costs.

In Québec, the provincially-owned utility Hydro-Québec has minimally unbundled its transmission system to comply with FERC rules in order to export to U.S. electricity markets. However, competitive wholesale markets have not been formed and the remainder of the system has not been liberalized. New Brunswick, which is home to a single reactor, fully unbundled its provincial utility in 2003 but vertically reintegrated it in 2013. This is the sole case of rebundling found in the sample. Like Québec, New Brunswick has never established competitive wholesale electricity markets.

In the United Kingdom, subnational variation existed temporarily between 1990 and 1996—Scottish NPPs were held by an unbundled, state-owned entity separately from the English and Welsh plants. The only difference between the Scottish and English & Welsh electricity sector during this time was the existence of wholesale spot markets in England & Wales and their absence in Scotland. This arrangement was revised in July of 1996 when the nuclear holdings were re-arranged on the basis of plant design rather than geography; plants of the MAGNOX design were retained by a state-owned company while plants of the AGR design and one PWR were privatized.

This obviously non-random assignment of reactors to one treatment or the other is the primary impediment to credible causal identification on the basis of subnational variation within the United Kingdom. A cross-national comparison of British nuclear is also stymied by the relative rarity of gas-cooled, graphite-moderated reactors (abbreviated simply GCR)[7] most common in Britain. While France built ten such reactors (including one in Spain), none are comparable in age to British AGRs ("advanced GCR") and all of them were retired

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[7] These should not be confused with the *water-cooled*, graphite-moderated reactors of the Soviet Union.

prior to or during the early nineties. Two British-designed GCRs were built outside Britain: one in Italy, which was forced to retire prematurely in 1987 when the Italian public approved a moratorium on nuclear power, and one in Japan, which retired in 1998.

The modal country history is for all reactors to begin their lives as the property of vertically integrated, government-owned utilities and–after restructuring–to operate as unbundled state-owned enterprises in competitive wholesale electricity markets. Two major exceptions to this are as follows:

In Japan, all reactors were owned and operated by privately-owned, vertically integrated utilities.[8] A competitive, independently-managed wholesale electricity market was established in 2005 but all utilities remain vertically integrated. Japan is noteworthy by itself as it has built nearly 10% of all reactors globally, nearly all of which are of designs imported from the United States.

Unbundling was always a feature of the nuclear power sector in Argentina, India, Pakistan, and China. Nuclear power plants in these countries were originally owned and operated by government agencies specifically dedicated to all things nuclear, including not only the construction and operation of nuclear power plants, but also nuclear weapons program, the nuclear fuel cycle, and nuclear medicine. These arrangements persist in India and Pakistan but are no longer in effect in Argentina and China.[9]

Several of the 38 countries in the sample enter and exit the panel at various times rather than being represented throughout the period of data availability (1970 to 2017). This largely a consequence of the collapse of communist governments in Eastern Europe after the fall of the Berlin Wall. The electricity market structure of predecessor nations and successor nations were researched and compared to determine if any discontinuity in industry structured occurred at the same time as regime change. In general, all reactors in post-

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[8] Excepting a few tiny demonstration plants and experimental reactors, which were built and operated by the Japan Atomic Energy Agency.

[9] In China, peaceful uses of the atom were separated from weapons development with the creation of state-owned enterprises solely focused on designing, building and operating NPPs. Argentina renounced its nuclear weapon ambitions after its military dictatorship ended in 1983.

communist countries continued under a similar industry structure in the immediate aftermath of regime change.

While regime change was not found to predict or determine restructuring, the directives of the European Union have clearly been a major driver of restructuring in several European nations. I group European countries into three groups: (1) "early adopters" of restructuring, (2) "reluctant adopters" and (3) EU accession nations. The early adopters consist of the United Kingdom, Spain, Sweden, and Finland, which adopted restructuring more comprehensive than required by the EU and/or well in advance of EU deadlines. Reluctant adopters are defined as France, Belgium, the Netherlands, and Germany, typically only complying with the bare minimum required and no sooner than the deadline set by the EU. Switzerland, while not an EU member and therefore not subject to EU regulations, chose to comply with EU rules in order to be able to participate in its neighbors' electricity markets. I classify it as also a "reluctant adopter" because it adopted wholesale competition and unbundling years after those were required by the EU. The final category of European nations consists of those which undertook electricity market liberalization in order to satisfy the requirements for accession to the EU. Among those with nuclear power plants are Slovenia, Czechia, Slovakia, Hungary, Lithuania, Romania, and Bulgaria, which collectively account for 28 reactors. In these cases, the argument for the exogeneity of restructuring is clearest: the desire to join the EU likely overrode any domestic political preferences (and industry lobbying) concerning the structure of the electricity sector.

Globally, among nuclear power plants, ownership unbundling is found predominantly in the United States and the United Kingdom. While ownership unbundling of other types power plants is fairly common in other jurisdictions, my research has found it is very rare for nuclear power plants. When state-owned plants are unbundled, they nearly always remain state-owned and therefore do not change ownership. When investor-owned plants are unbundled, they tend to remain under the corporate umbrella of their former vertically-integrated utility, particularly in continental Europe. Only the occasional acquisition or merger gives rise to ownership unbundling of NPPs in jurisdictions outside of the US and UK. Therefore, because ownership unbundling is quite rare and leasing is only observed at a single plant, for the puruposes of the current analysis, I code all plants which are legally unbundedl, ownership unbundled, or leased as simply `unbundled`.

4 Data

I assembled a database of all commercial nuclear power reactors which have ever been brought into operation, as of December 31st, 2017. 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. Thus, the dataset I have assembled offers considerably more detail and comprehensiveness than any other prior work on this topic, to my knowledge. Unfortunately, the terms and conditions of my access to PRIS prohibit me from sharing any of its data that is not otherwise publicly available.

The IAEA PRIS database consists of 1,056 observations (reactors). Of those, several hundred were not suitable for analysis, for one of the several possible reasons: (1) the reactor is "in planning" (announced to be built or speculated may be built), (2) the reactor was still under construction as of the time of data collection (summer 2018), (3) construction or commissioning of the reactor was abandoned before entering commercial operation, or (4) reliability data were not supplied to IAEA for the reactor. Out of the 623 reactors which passed the first three criteria, the number of reactors with any reliability data was 592.

Because the data for each observation in PRIS is entered 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 personal knowledge of the subject matter to clean up the data where an inconsistency was apparent. 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 of designed and manufactured by this company are not consistently labeled under a single name in the raw PRIS dataset.

4.1 Measures of Reliability

I select as my dependent variables two measures of reliability, the energy availability factor (EAF) and the unplanned capability loss factor (UCL). Following the PRIS codebook provided by IAEA, they are defined as follows:

$$\text{EAF} = \frac{\text{energy generated} + \text{energy available but not supplied}}{\text{reference energy generation}}$$

$$\text{UCL} = \frac{\text{unplanned energy losses}}{\text{reference energy generation}}$$

Reference energy generation is the theoretical maximum that could be produced assuming the plant operated under full power for the entire period. Energy available but not supplied refers to the potential energy that the plant could have generated if the grid operator had called on it to operate for longer and/or at a high power level. Unplanned energy losses refers to energy not generated due on-site conditions attributable to plant management, such as an equipment failure. UCL is not identically equal to $100\% - \text{EAF}$ because it does not include energy unavailable for reasons outside of the control of plant management.

Although capacity factor is a direct measurement of output, I do not evaluate it because it is simultaneously determined by demand and supply. In most countries, the effect of demand on the capacity factors of NPPs is trivial, as nuclear power constitutes a small enough fraction of the total supply that it always operates in a baseload condition. However, this is notably not the case in France, where 71.7% of all electric generation was derived from

Table 1: Output and Reliability of NPPs by country, 2009-2018

Country	**CF (%)**	**EAF (%)**	**UCL (%)**	**N**
Finland	92.4	92.1	1.7	4
United States	90.7	90.8	1.9	105
Spain	86.4	86.4	3.0	8
China	84.8	89.0	0.9	43
World Average	**81.7**	**82.9**	**4.6**	**496**
Russia	81.6	81.0	2.7	38
South Korea	80.1	80.8	1.5	25
Canada	79.8	80.4	5.3	20
Germany	79.5	83.0	7.0	17
United Kingdom	74.9	74.6	13.3	19
France	73.0	75.4	8.9	59

Average capacity factor (CF), energy availability factor (EAF), and unplanned capability loss factor (UCL) of nuclear power plants for selected countries, over the years 2009 and 2018, inclusive. The "world average" excludes Japan, which required many of its nuclear power plants to cease operation until receiving approval to restart following the Fukushima Daiichi meltdown in 2011.

nuclear power in 2018; other countries with high nuclear shares include Slovakia (55%) and Hungary (51%).[10] In Germany, despite its relatively low and declining share of electricity from nuclear power, NPPs are frequently called on to perform load-following operations to accommodate intermittent renewable energy (Lokhov, 2011). Therefore, I have chosen to analyze reliability rather than output *per se*, because reliability is a necessary precondition to output that is not co-determined by demand or competition from lower-marginal-cost generation.

Unlike Davis and Wolfram (2012), I do not hold reference energy generation constant over time; it instead evolves as the reactor's capacity is uprated or downrated. I do this for two reasons. First, the reliability data provided by IAEA have do not hold reference energy generation constant over time. To mirror the method of Davis and Wolfram (2012), it would be necessary to acquire the history of uprates and downrates for the global population of nuclear reactors. Such data, if they exist, were not made available to me by IAEA. Second, the treatment effect estimated by Davis and Wolfram (2012) was predominantly driven by

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[10] Source: PRIS. `https://pris.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=FR`

improvements in reliability, and only secondarily by updates.

Recent summary statistics for capacity factor, energy availability factor, and unplanned capability loss factor for several countries of interest are presented in Table 1. Figure 1 displays the global trends in EAF and UCL since 1970. Both exclude trimmed data (see Section 5.1 below for explanation).

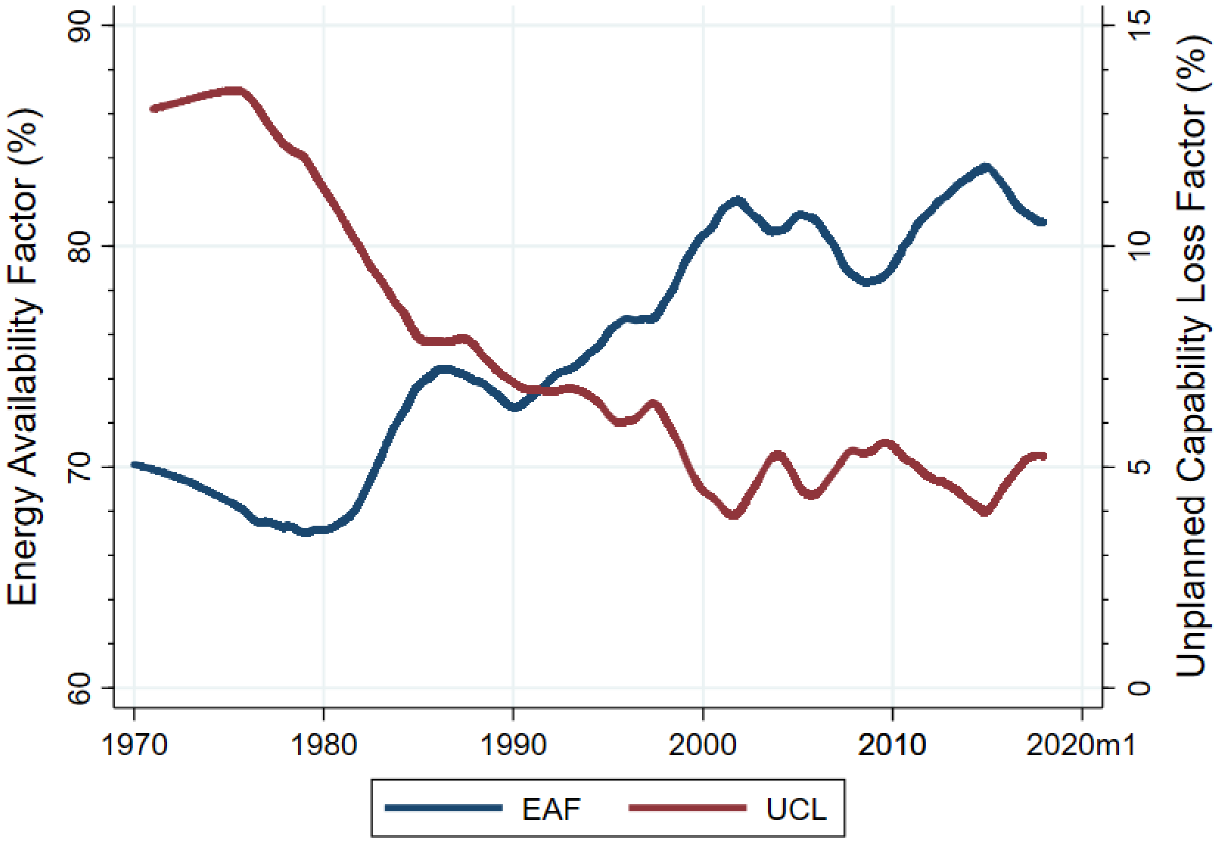

Figure 1: Global trends in NPP reliability, excluding trimmed data (see section 5.1/ Data Source: IAEA PRIS.

The industry-wide improvements in reliability cannot be purely explained by the entry of improved designs of NPPs into the market, exit of poorly performing plants, or a increased representation of high-reliability countries in the population of operational NPPs. Table 2 reports regressions which establish that reliability has been trending upwards, even when controlling changes in the composition of countries and reactor designs represented in the global population over time. The apparent interpretation of the data is the industry's upward trend is at least in part explained by improvements in reliability of existing plants.

Table 2: Secular Improvement in NPP Reliability

	(1)	(2)	(3)	(4)
Current Year of Operation	0.288*** (0.044)	0.288*** (0.044)	0.288*** (0.044)	0.285*** (0.045)
Year Construction Began	0.313*** (0.090)	0.297** (0.096)	0.377*** (0.112)	(omitted)
Reactor Type Fixed Effects	No	Yes	No	No
Reactor Model Fixed Effects	No	No	Yes	No
Reactor Fixed Effects	No	No	No	Yes
Month Fixed Effects	Yes	Yes	Yes	Yes
Country Fixed Effects	Yes	Yes	Yes	No
N	592	592	592	592

The dependent variable in all four regressions is energy availability factor (EAF), a standard measure of reliability defined in Section 4.1. Standard errors are clustered by plant (one plant may include multiple reactors). In model (4), all time-invariant characteristics are dropped due to reactor fixed-effects.

4.2 Control Variables

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 (after uprates and downrates), the current gross electric capacity (prior to netting out on-site consumption of electricity), and the current rating of the thermal capacity (a measure of the core's ability to produce heat, prior to conversion to electricity). Any intermediary capacity ratings between the original and current ratings are not reported; moreover, the timing of uprates and downrates is also not reported. In my preferred specifications, I use current net electricity capacity. The largest share of the data tends to be most recent—far more reactors enter the sample in later years than leave it, and data coverage of developing countries and (post-)communist countries improves with time. In any case, the choice is of little practical significance, as the four available measures of capacity are tightly correlated, exhibiting a Pearson's r of .99 in every pairwise comparison.

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)(347 obs.), boiling water reactors (BWR)(116 obs.), pressurized heavy water reactors (PHWR)(57 obs.), gas-cooled reactors (GCR)(52 obs.), and light water graphite reactors (LWGR)(30 obs.). All other types were aggregated into a category called "other" due to a sparsity of observations (21 obs.).[11]

Reactor Model: the name of the model assigned by the manufacturer. For example, AP-1000, CP1, P4, OPR-1000, CNP-300, VVER-1000, and SNUPPS. In many cases, particularly for non-standardized design, PRIS instead provides an abbreviated, generalized description. For example, "WH 4LP (DRYAMB)" indicates that the reactor is a Westinghouse design with four primary coolant loops and the containment structure is of a "dry, ambient pressure" design.

Manufacturing Firms: the manufacturer(s) of the nuclear steam supply (NSSS), the manufacturer(s) of the steam turbines, and the national origin of each firm.

Design Specifications: over 150 characteristics[12] of the design, such as cooling method (e.g. cooling towers vs. once-through cooling), height and diameter of the reactor pressure vessel, number of reactor coolant loops, containment design, volume of the containment, and average core power density. Unfortunately, many of these variables were left blank for a large number of the observations. Certain variables offer greater data coverage than others. Where possible, missing data was supplemented by my own research. See Benson (2019a) for details.

Overnight Capital Cost: Overnight capital cost is the accounting cost—i.e. excluding

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[11] The term "heavy water" refers to water whose hydrogen atoms contain an additional neutron. "Light water" refers to ordinary water. BWRs and PWRs are both light water reactors, although "light" is traditionally omitted from their names and acronyms.

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

the opportunity cost of capital (or actual interest payments, if debt-financed) for funds to pay for construction prior to the beginning of commercial operation. I rely on the data compiled by Portugal-Pereira et al. (2018), which is inflation-adjusted to 2010 US dollars.

Construction Lead Time: PRIS reports the dates of construction start, first criticality, first grid connection, and the first day of commercial operation. Lead time was computed from the difference between construction start and commercial operation.

5 Methods

5.1 Data Trimming

I trim the data in two major ways before proceeding with further analysis.

First, I drop all 21 reactors classified as the type "other," per the definition in Section 4.2. These other types of reactors primiarily small pilot experiments. A few of them are quite large and were intended to generate electricity commercially, but so far plants of their design have not yet replicated to meaningful extent. This makes them unsuitable for comparison with similar reactors, as each one is essentially one-of-a-kind. Furthermore, reactors of these types tend to be more unreliable than the other types, either due to their purpose as experiments or due to inherent design flaws that caused them not to be selected for commercialization. In Table A1, I report a simple regression of EAF on reactor type with year fixed-effects, reactor random-effects, and standard errors clustered by plant. Reactors of the "other" type exhibit reliability on average 31 percentage points lower than PWRs, the modal type of reactor.

Second, I trim all data from Japanese reactors as of March 2011 or after. The Great Tohoku Earthquake occurred on March 11th, 2011, precipitating the tsunami that caused the meltdowns at the Fukushima Daiichi Nuclear Power Plant. Since that time, the government of Japan has suspended operations at nearly all its other nuclear power plants, pending regulatory and political determinations of whether they may resume operations.

As of August 2019, only nine are currently operating, out of 59 ever built and operated.[13] So long as the remainder are held in limbo—not retired and not yet permitted to resume operation—IAEA records their EAF as 0%. Given that the cause of their inability to operate is neither technical nor economic in nature, I conclude that my model is ill-suited to account for their apparent "low reliability." Fortunately, the actual cause is self-evident and does not require complex statistical analysis to identify. In the interests of improving the precision of the model, I therefore omit all Japanese reactors from March 2011 onward, including those that have been permitted to restart, to avoid any possible selection bias.

5.2 Fixed Effects

I begin with the two-way, fixed-effects strategy of Davis and Wolfram (2012). However, I depart from them in a several notable ways. Whereas they control for month-of-sample fixed effects, I control for month-of-year fixed effects and year-of-sample fixed effects separately. I argue that year fixed effects should be sufficient to capture macroeconomic shocks and long-term, industry-wide trends in NPP reliability. However, I still include month-of-year fixed effects to account for seasonality, which is the overriding explanation for month-to-month variation in NPP operations. Nuclear power plants tend to schedule their refueling and maintenance outages during months of low electricity demand. For most countries, this is the spring and the fall, when the weather is mildest.

In pursuit of even more precise estimation of seasonal patterns, I tested month-by-climate fixed effects in preliminary regressions involving no treatment variables. I matched each plant by latitude and longintude to Köppen climate classification data from Chen and Chen (2013). The Köppen climate classification system consists of 31 unique climates, of which 17 appear in the data once matched with nuclear power plants. To avoid overfitting, I collapsed the climate classifications to the top 5 groups defined by their first letter (A - tropical, B - desert,

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[13] World Nuclear Association. *Nuclear Power in Japan.* `https://world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.aspx` Accessed September, 14, 2019.

C - temperate, D - continental, E - polar).

However, this specification was ultimately rejected. The between-R^2 is substantially higher for the more parsimonious model than the more complex model, 0.17 and 0.06, respectively. The more complex model offers only trivial improvement in within-R^2, 0.025 as compared to 0.024. In other words, climate-by-month fixed effects only marginally improve estimation of within-reactor (i.e temporal) variation in reliability while soaking-up a large amount of the between-reactor (i.e. cross-sectional) variation in reliability, submerging them in unexplained fixed-effects. Graphical inspection of the separately estimated seasonal patterns for each climate group revealed that the seasonality of nuclear power plant operation in deserts, tropical regions, tundra, and even the Southern Hemisphere (for which I included a separate set of month fixed effects) do not vary too greatly from the seasonality typical of plants in temperate regions of the northern hemisphere, where the majority of nuclear power plants have been built. The results of the two models are reported in Table A2 of the appendix.

Davis and Wolfram (2012) rely on reactor fixed effects to control for unobserved, time-invariant characteristics of each reactor that could affect reliability. Below, I report a result with reactor random effects, because the random model permits the inclusion of control variables capturing reactors' time-invariant characteristics described in Section 4.2. Primarily, I include *reactor model* fixed effects. As defined in 4.2, these are alphanumeric classifications of a reactor's design provided by either the manufacturer or IAEA. Excluding the trimmed reactors of "other types," there are 98 unique reactor models. Given 574 reactors present in the trimmed data, that results in an average of 5.85 reactors per model.

However, as discussed in Section 6, the Durbin-Hu-Hausman test and an additional test indicate that reactor fixed effects should be preferred due to possible inconsistency of random effects. Therefore, I report results with reactor fixed effects.

To enable cleaner comparisons of my results with those of Davis and Wolfram (2012) for the purpose of replication, I control for a cubic polynomial of reactor age in unreported regressions. However, my preferred specification controls on the log of reactor age, as most regressions do not return statistically or economic significant coefficients on the cubic term. In several cases, my statistical software drops the cubic term from the estimation, reporting multicollinearity. I also modify their approach slightly by interacting reactor age with reactor type. This allows for the possibility that the effect of aging on reliability may be more pronounced for certain types of reactors than others, particularly those which tend to have shorter operational lives, such as pressurized-heavy water reactors.

5.3 Causal Identification

The primary empirical challenge to estimating the casual effect of electricity market restructuring is non-random assignment of the policy. For the United States, Davis and Wolfram (2012) suggest "that the best predictors [of deregulation] are liberal politics and high electricity prices." However, they do not estimate an instrumental variables regression to test such a hypothesis. I propose several instruments for the United States, and one for the European Union.

In (Benson, 2019b), I find that liberal politics are strongly positively related with nuclear power plant construction outcomes in the United States, specifically overnight capital cost and lead time. Because of the capital intensity of nuclear power plants, their budget overruns and schedule delays can dramatically grow the ratebase of vertically-integrated utilities which regulated on cost-of-service principles. A larger ratebase without proportionately higher demand results in higher electricity prices for consumers. As argued by Borenstein and Bushnell (2000), one of the principal motivations for electricity market restructuring in the United States was the desire to reallocate sunk costs—including, but not limited to, nuclear power plant construction costs—from consumers to utility shareholders by switching from average-cost to marginal-cost pricing. In Table 3, I report the results of a logit regression of whether a US reactor was ever restructured on a state-level measure of liberal politics[14], the

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[14] I rely on the "state policy liberalism" score compiled by the Correlates of State Policy Project (Jordan

Policy Outcome:	Divestiture	Divestiture	Wholesale Competition	Wholesale Competition
Government-owned utility	-2.66* (1.16)	-2.38* (1.18)	-3.38** (1.18)	-2.96 (1.74)
State policy liberalism, as of 1996	0.95* (0.46)	0.99 (0.57)	1.91*** (0.44)	2.15*** (0.49)
ln(Construction lead time)	1.44* (0.60)	1.07* (0.87)	1.56 (0.93)	1.24 (1.40)
ln(Overnight capital cost)	-0.32 (0.39)	0.14 (0.57)	-0.27 (0.65)	0.03 (0.70)
average EAF prior to FERC Order 888 (1996)		-0.00 (0.03)		0.03 (0.03)
N	126	126	126	126

Table 3: Logit regression model predicting the exposure of US nuclear power reactors to electricity sector restructuring. The dependent variable is a binary indicator of whether the reactor has ever been treated by the policy.

plant's overnight capital cost, construction lead time, and its average reliability up to the year 1996 (when Order 888 was approved by FERC, which set the stage of electricity sector liberalization in the United States).

In Europe, a leading driver of the adoption of electricity restructuring policies was a series of directives of the European Union, policies which require EU member states to achieve a particular policy outcome with flexibility in the policies used to achieve it. These began with directive 96/92/EC in 1996, which began the process of cross-national grid integration and established the first, albeit minimal, rules to promote fair access for third-parties to the transmission grid. This was followed up by 2003/54/EC, according to which all EU members were obliged to legally unbundle their transmission and distribution systems by July 1st, 2004 (if they had not already done so). With 2009/72/EC, the unbundling requirements were ratcheted up to require either ownership unbundling or management of the grid by an independent entity. As discussed in Section 3.2, several EU members were in compliance with

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and Grossmann, 2016).

these regulations well in advance of their promulgation. Others were obliged to liberalize as a consequence of the policies. This suggests the possibility of unobserved differences between the early-adopter and the reluctant compilers which could effect both the timing of their policy reforms and their electricity sectors. Therefore, in Europe, I instrument for the adoption of unbundling using an indicator variable that takes on the value 1 in all months including and after the later of either EU accession or July 2004, or 0 otherwise. (Note: this variable always takes on the value zero in all countries which have never acceded to the EU.)

This instrument for Europe offers relatively little within-Europe variation in the treatment, as several Eastern European nations acceded to the EU on May 1st, 2004 and two acceded on January 1st, 2007. The only European nations with nuclear power plants outside the EU are Switzerland (5 obs.), Ukraine (17 obs.), and Russia (36 obs.). While Ukraine and Russia would seem to represent a promising control group against which to compare Eastern European nations that acceded to the EU (especially in light of the fact that many of them operate reactors of Soviet design), these two countries did in fact adopt electricity liberalization voluntarily.

However, more institutional history can be exploited to instrument for the industrial organization of nuclear power in the Soviet Union and its successor states. In July of 1986, two months after the Chernobyl disaster, ownership and operation of the nuclear power plants of the Soviet Union were transferred from the Ministry of Energy (MinEnergo), which was responsible for the state-owned, vertically-integrated electric utility, to the newly created Ministry of Atomic Energy (MinAtom). I classify this in my dataset as a legal unbundling. This arrangement (unbundling & state ownership) persists to the present day for all nuclear power plants the former Soviet Union and was not interrupted or modified as a result of regime change. The Chernobyl disaster did not trigger unbundling or other administrative reforms in fellow Warsaw Pact nations, perhaps in part because the RBMK design at Chernobyl was never exported outside of the Soviet Union.[15] Thus, unbundling can

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[15] The RBMK is of a LWGR reactor type. The Soviet Union only exported PWR-type reactors to its allies.

be instrumented for in Russia, Ukraine, Latvia, Armenia, and Kazakhstan. However, the introduction of competitive electricity markets remains potentially endogenous.

6 Results

Table 4 reports the results of several regression specifications in which EAF is the outcome of interest. (The equivalent table for UCL is provided in the appendix.) In column (1), I report coefficients of interest from a fairly basic model; notably, the treatments are not instrumented and reactor fixed effects are omitted in favor of reactor model fixed effects. In Column (2), I introduce reactor fixed effects, which forecloses estimation of any time-invariant variables. A Durbin-Wu-Hausman specification test was performed to compare model (1) against model (2); the resulting test statistic rejects the null hypothesis (p¡.0001) that model (1) is consistent and model (2) should be preferred as the fixed-effects estimator is known to be consistent. This comes at a significant cost of efficiency, increasing the standard errors on the coefficients of interest. However, the Hausman test requires the assumption of homoskedasticity, whereas all models reported here were estimated with clustered standard error, with errors clustered by by plant (recall that one plant may host more than one reactor). Furthermore, it is notable that none of the coefficients of interest (those on the indicator variables for electricity sector structure) are statistically different from each other. Close inspection of the calculation of the Hausman test statistic reveals that it is primarily driven by differences in the estimated year-fixed effects.

For greater confidence in the result of the model selection, I conducted a second test, that which was proposed by Mundlak (1978), which is robust to heteroskedasticity and can isolate whether the regressors of interest are correlated with unobserved time-invariant characteristics. The procedure is as follows: for each reactor, I calculated the average value of each treatment variable (unbundling, presence of wholesale competition, private ownership) over all observations for that reactor. This time-invariant average is then assigned as a new

		(1)	(2)	(3)	(4)
Government-Owned NPPs					
Unbundled	Wholesale Competition				
No	No	*omitted reference category*			
Yes	No	-5.07*	-6.07**	-4.59	-6.02
		(2.05)	(2.19)	(2.44)	(6.99)
No	Yes	-3.69**	-3.46*	-15.04***	14.38***
		(1.35)	(1.38)	(2.60)	(3.36)
Yes	Yes	-0.39	-0.61	4.16	11.41**
		(1.63)	(1.76)	(2.95)	(3.53)
Privately-Owned NPPs					
Unbundled	Wholesale Competition				
No	No	0.08	0.58	5.27*	6.48*
		(2.17)	(3.57)	(4.25)	(2.88)
Yes	No	3.87	4.46	-15.29***	13.02***
		(3.62)	(4.12)	(3.73)	(2.69)
No	Yes	-3.32	-2.63	12.50**	6.38
		(2.93)	(3.78)	(3.77)	(3.05)
Yes	Yes	5.46*	6.09	10.67*	13.90***
		(2.51)	(3.39)	(3.92)	(2.69)
Control Variables					
ln (reactor capacity)		1.13	*cannot be estimated with reactor fixed effects*		
		(3.58)			
Once-through cooling		-3.81**	*cannot be estimated with reactor fixed effects*		
		(1.30)			
RBMK design × post-Chernobyl		-9.89***	-9.22**	*N/A*	*N/A*
		(2.74)	(2.87)		
ln (reactor age) × reactor type		Yes	Yes	Yes	Yes
Reactor model fixed effects		Yes	*cannot be estimated with reactor fixed effects*		
Reactor Effects		Random	Fixed	Fixed	Fixed
Year-of-sample fixed effects		Yes	Yes	Yes	Yes
Month-of-year fixed effects		Yes	Yes	Yes	Yes
Countries included		All	All	GBR, ESP, SWE, FIN	USA, CAN
Reactors (i)		552	552	69	139
Months (t)		576	576	576	576
Observations (n)		179,711	179,711	25,134	54,889

Table 4: Regression results for the main models. Models (3) and (4) are geographically restricted. Model (3) only includes reactors in European countries which liberalized their electricity sector in the 1990s (United Kingdom, Spain, Sweden, and Finland). Model (4) only includes reactors in North America.

variable to every observation. These new variables are included in the random effects regression, along with the actual, time-varying treatment variable. If the coefficients of the newly generate variables are statistically different from zero, then it suggests that assignment to treatment is correlated with time-invariant unobserved characteristics that affect the outcome. The results of the Mundlak procedure for model (1) indicate that the average levels of unbundling and the introduction of wholesale competition, but not private ownership, within panels (reactors) are correlated with time-invariant unobserved characteristics which are associated with higher (for unbundling) and lower (for wholesale competition) levels of reliability. Therefore, I conclude that I must use reactor fixed-effects to avoid omitted variables bias. Models (2) through (4) all use reactor fixed effects.

In model (4), I restrict the model to North America.[16] The results are quite striking when compared to the global average. The first result to observe is that unbundling (whether paired with wholesale competition or not) appears to have greatly improved reliability for publicly-owned reactors in North America as compared against the global average. Next, note that the typical privately-owned, unrestructured reactor (all of which are found in the US) appears to perform 6 percentage points more reliably than its publicly-owned peers in North America. However, this particular coefficient is not terribly credible in light of the fact that is only estimated off of privatizations at three plants (11 reactors): Fitzpatrick and Indian Point Unit 3 in New York, and Bruce in Ontario (where ownership remained public but the lessee is a private firm). Relative to this higher baseline, unbundling (with or without wholesale competition) raises the reliability of privately-owned plants by 6.5 to 7.5 percentage points.

For government-owned plants, the combination of unbundling and wholesale competition is estimated to have had an even stronger effect, at an 11 pecentage points increase in EAF. Wholesale competition without unbundling appears to have the strongest effect of all, but this is estimated purely off of the six years and three months during which South Texas Units

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[16] Specifically, the United States and Canada. Mexico is not considered part of North America for the purposes of this analysis.

1 and 2 operated in competitive wholesale electricity markets prior to unbundling in 2003. Unbundling without wholesale competition seems to produce a statistically insignificant effect on reliability for publicly owned plants that is quantitatively similar to the effect observed globally.

In the present draft, I do not report the results of any models with instrumental variables because of coding difficulties. Preliminary results suggest that the instrumental variables approach returns a different result (specifically, smaller effect sizes, possibly zero) but I have little confidence that the coding is correct at this time. Work is ongoing to refine the approach.

7 Conclusion and Plans for Future Research

The preliminary results produced so far indicate that the effect of electricity sector restructuring does substantially vary across jurisdictions. The United States and Canada stand out as exhibiting the greatest improvements in NPP reliability response to restructuring. For other countries, the effect of restructuring is more modest, only marginally statistically different from zero, or possibly negative in the event of partial restructuring.

There are several opportunities for near-term improvement to the current work. The first is to properly implement instrumental variables estimation. Another is to test for pre-treatment effects or a gradual post-treatment learning period.

More ambitiously, I plan to model learning over time, including within-plant, within-firm, cross-firm, within-country, and cross-country. These learning effects might be mediated by the degree of similarity in design across reactors. In the current research design, learning is not modeled because the plant's own past performance is a function of past values of the treatment, which is highly correlated with the current value of the treatment. Methods suitable for dynamic panel data, such as the Arellano-Bond estimator, will need to be employed.

Another opportunity for improvement is incorporating terms in the model which capture plant-specific serial correlation, particularly serial correlation arising from refueling cycles, which are typically 12, 18, or 24 months in length. Unreported preliminary results strongly support the hypothesis the the patterns of serial correlation vary based on refueling cycle. As above, this requires more sophisticated modeling and econometrics to properly account for the dynamic nature of the data.

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