Deregulation, Consolidation, and Efficiency: Evidence from U.S. Nuclear Power

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Abstract

For the first four decades of its existence the U.S. nuclear power industry was run by regulated utilities, with most companies owning only one or two reactors. Beginning in the late 1990s electricity markets in many states were deregulated and almost half of the nation's 103 reactors were sold to independent power producers selling power in competitive wholesale markets. Deregulation has been accompanied by substantial market consolidation and today the three largest companies control more than one-third of all U.S. nuclear capacity. We find that deregulation and consolidation are associated with a 10 percent increase in operating efficiency, achieved primarily by reducing the frequency and duration of reactor outages. At average wholesale prices the value of this increased efficiency is approximately $2.5 billion annually and implies an annual decrease of almost 40 million metric tons of carbon dioxide emissions.

Key Words: Market Deregulation, Operating Efficiency, Nuclear Safety
JEL: D22, D40, L51, L94, Q48

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1. Introduction

Market deregulation has been one of the dominant economic trends worldwide over the last 30 years. Economic theory implies that competition provides incentives for firms to increase efficiency, cut costs, and make prudent investments in capacity and technological innovation. A broad literature has developed in economics evaluating this transformation from both theoretical and empirical perspectives. Among the markets that have received the most attention are airlines, financial services, telecommunications, transportation and energy.[1]

Over this period many industries have also been characterized by large increases in the degree of market consolidation. Here economic models describe a tradeoff between economies of scale and the ability of larger firms to exercise market power. Again, government plays a central role, with antitrust policies determining the degree of concentration in a variety of different important markets. An extensive literature in industrial organization provides a guide for assessing the impacts of consolidation on market outcomes. Though firms confronting a potential merger review often argue that there will be efficiencies from consolidation, there is comparatively little theory or evidence evaluating such claims.[2]

This paper examines an unprecedented period of deregulation and consolidation in the U.S. nuclear power industry. For four decades all nuclear power reactors in the United States were owned by regulated utilities. Few utilities owned more than one or two reactors and utilities received a rate of return on their capital investments that was largely disconnected from operating efficiency. Beginning in the late 1990s electricity markets in many states were deregulated and 48 of the nation's 103 nuclear power reactors were sold to independent power producers selling power in competitive wholesale markets. These divestitures have led to substantial market consolidation and today the three largest companies control more than one-third of all U.S. nuclear capacity.

There are a number of reasons why the nuclear power industry is a particularly good candidate for a study of the relationship between deregulation, consolidation, and efficiency. First, electricity is a homogeneous good that is accurately and consistently

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[1] See Joskow and Rose (1989), Winston (1993), Peltzman and Winston (2000), and Joskow (2005) for reviews of this literature.

[2] Several papers examine the interplay between market structure and efficiency including Olley and Pakes (1996), Borenstein, Bushnell and Wolak (2000)etc., . Most of these papers focus on reallocations across firms.

measured across space and time, eliminating concerns about differences in quality that make it difficult to measure efficiency in many markets. Second, during the relevant period there is very little entry or exit of nuclear reactors, mitigating concerns about selection that substantially complicate similar analyses. Third, nuclear reactors produce electricity at very low marginal cost so they are always considered "baseload" generation, and fluctuations in demand are essentially irrelevant. Fourth, that deregulation and consolidation occurred rapidly and for only half of all reactors lends credibility to the empirical analysis, facilitating comparisons both across reactors and over time.

Using a unique 40-year monthly panel of all nuclear reactors in the United States we find that deregulation and consolidation are associated with a 10 percent increase in operating efficiency, achieved primarily by reducing the frequency and duration of reactor outages. Efficiency gains were experienced broadly across reactors of different types, manufacturers, and vintages, with the largest effects in the spring and fall during the peak months for refueling. We also examine explicitly the role of consolidation, comparing efficiency gains across companies that operate different numbers of reactors. While we find evidence that consolidation led to improved operating efficiency, it explains very little of the overall increase.

Our results imply a substantial increase in electricity production. In 2009 U.S. nuclear reactors produced 800 billion kilowatt hours of electricity, about 20% of total U.S. electricity generation. We estimate that the increase in electricity production due to deregulation and consolidation exceeds 40 billion kilowatt hours annually. At current average wholesale prices, the value of the increased electricity production is approximately $2.5 billion annually. This increase is almost pure efficiency gain, achieved without building a single new plant or constructing a single additional mile of transmission capacity.

In addition, because the increased electricity production displaces mostly coal- and natural-gas- fired power, these gains in efficiency also have substantial implications for the environment, implying an annual decrease of 38 million metric tons of carbon dioxide emissions. Using a conservative estimate for the social cost of carbon dioxide ($20 per ton) this is an additional $760 million in benefits annually. To put this into perspective, this is more carbon abatement than was achieved by *all* the U.S. wind and solar generation combined during the same period. Whereas there are explicit programs directed at promoting low-carbon energy in the case of wind and solar, this decrease in carbon emissions is noteworthy because deregulation is not usually envisioned as a means for achieving environmental goals.[3]

Finally, we perform a similar analysis for an available measure of reactor safety. Whereas economic theory provides clear predictions for operating efficiency, the effect of deregulation on safety is ambiguous and depends on whether safety is a complement or a substitute to operating efficiency (MIT 2003, Hausman 2011). We find that divestiture and consolidation are associated with a *decrease* in the number of safety-related automatic shutdowns, also known as "scrams". The point estimate is not statistically different from zero (*p*-value .09), but is precisely enough estimated to reject small (>5%) increases. Safety is inherently much more difficult to measure than operating efficiency and although we view these results as suggestive, scrams are a highly imperfect measure of safety and as more and richer data become available it will be important to revisit this important issue.

Our results are relevant to current policy discussions about the future of U.S. nuclear power. Concerns about climate change, energy security and volatile fossil-fuel prices have emboldened proponents of nuclear power, with some even forecasting a nuclear "renaissance." No new reactors have come online in the United States since the mid-1990s, but between 2007 and 2009 the Nuclear Regulatory Commission (NRC) received license applications for 26 proposed new nuclear reactors.[4] Several recent studies (MIT 2003, MIT 2009, Joskow and Parsons 2009) compare the lifetime costs of nuclear to other generating alternatives and highlight the importance of nuclear operating efficiency in these calculations.

The format of the paper is as follows. Section 2 provides relevant background information about the nuclear power industry and the broader electricity market. Sections 3 and 4 describe the data and empirical strategy. Section 5 includes the main results, presenting estimates of the effect of divestiture and consolidation on nuclear reactor efficiency for a variety of different specifications including a set of regressions aimed at addressing potential concerns about selection bias. Section 6 presents additional results aimed at attempting to better understand the mechanisms driving the increase in efficiency,

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[3] Moreover, estimates from Borenstein (2008) and Joskow (2011) imply that to have obtained this same level of carbon abatement through wind or solar generation would cost more than $10 billion annually. Borenstein (2008) calculates an implied carbon dioxide mitigation cost of $300-600/ton for rooftop solar photovoltaics. Joskow (2011) calculates an implied carbon dioxide mitigation cost of $300/ton for the Cape Wind offshore wind project.

[4] See Table 9 in U.S. NRC. "Information Digest 2010-2011" NUREG-1350, Volume 22, published August 2010.

including ancillary evidence on investments in reactor capacity as well as on the frequency, duration, and type of outages. Section 7 offers concluding comments.

2 Background

2.1 Nuclear Power and Wholesale Electricity Markets

Electricity is supplied using several different generating technologies. In the United States the most important sources in terms of total electricity production are coal (45%), natural gas (23%), nuclear (20%), hydro (7%), and wind, solar, and other renewables (4%).[5] Nuclear reactors are expensive to build, but then produce power at lower marginal cost than most other technologies. Coal and natural gas produce power at somewhat higher marginal cost, but require smaller initial capital investments.[6] The other key difference between nuclear and other forms of electricity generation is the ease with which output can be adjusted to meet variable electricity demand. Nuclear power reactors typically take several days to ramp up or ramp down, and thus are usually shut down only for refueling or maintenance. At the other end of the spectrum are natural gas peaking plants which can be turned on and off almost instantly and with essentially no startup cost.

These features imply that nuclear reactors are typically used to provide baseload power, 24 hours a day, 7 days a week. This explains why in the United States nuclear power accounts for only 10% of capacity but produces 20% of total electricity production.[7] As electricity demand peaks during the middle of the day, other forms of generation come online but nuclear reactors continue to generate power at the same level. Of course this depends in practice on the fraction of electricity generation that comes from nuclear. In the United States, this is a small enough share that even during the lowest consumption periods in the middle of the night there is enough demand to keep nuclear reactors operating. Nuclear plants are large so small improvements in operating efficiency imply substantial amounts of electricity. Consider, for example, a typical two-reactor 2000MW nuclear plant.

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[5] These shares are from 2009 according to U.S. Department of Energy, Energy Information Administration, “Annual Energy Review 2009”, released August 2010, Table 8.2a “Electricity Net Generation”.

[6] MIT (2009) reports fuel costs (per MWh) of $23 and $48 for coal- and natural gas-fired power plants but only $7 for nuclear power, based on fuel prices of $2.60, $7.00, and $0.67 per million BTU and average heat rates of 8870, 6800, and 10400 BTU per kilowatt hour, respectively.

[7] U.S. Department of Energy, Energy Information Administration, “Annual Energy Review 2009”, released August 2010, Tables 8.11a “Electric Net Summer Capacity” and 8.2a “Electricity Net Generation”. In 2009, nuclear power accounted for 9.8% of net summer capacity and 20.2% of total net generation.

At typical wholesale electricity prices ($60 per MWh), a plant that operates 80% of the year produces power worth approximately $840 million dollars annually. An increase from 80% to 85% increases revenues by $52 million dollars annually, $120,000 for each additional hour that the plant is operating. And this is essentially all profit. Average fuel costs for nuclear plants ($7 per MWh) are a small fraction of typical wholesale rates.[8] Besides fuel, most other inputs are fixed in the short run. For example, nuclear reactors keep a staff of salaried workers on site 24 hours a day, regardless of whether the reactor is online.

These features of the market imply that profit maximization for a nuclear reactor is very simple. The firm wants to run the reactor as much as possible. Where there are wholesale electricity markets, demand fluctuations will affect electricity prices, but not nuclear output. Similarly, the entry or exit of other generating units will typically have no impact on operation behavior for nuclear plants which in all cases remain as baseload generation. Moreover, because it is costly to adjust output, typically it will not make sense for operators of nuclear reactors to attempt to unilaterally exercise market power. The costs to a reactor operator of ending up outside the queue are simply too large to risk submitting bids above marginal cost. Instead, the real scope for market power comes from a firm that operates a portfolio of both nuclear reactors and other non-nuclear generating facilities such as natural gas peaking plants.

2.2 The Regulation and Deregulation of Electricity Markets

Traditionally electricity was regarded as a natural monopoly. In the standard regulatory model still used in many states today, investor- and, in some cases, municipally and federally-owned utilities receive exclusive rights to provide electricity within given geographic areas and are allowed to charge rates set by cost-of-service regulation. These vertically-integrated utilities typically perform all the activities required to supply electricity to residential, commercial, and industrial customers including generating electricity, operating the transmission and distribution networks, and providing retail services such as billing and customer service.

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[8] This includes ore purchase, yellow cake conversion, and enrichment (MIT 2009). Fuel costs are by far the largest component of variable operating costs for nuclear plants. Variable operations and maintenance costs (excluding fuel) are $0.51 per MWh according to U.S. Department of Energy, Energy Information Administration, "Assumptions to the Annual Energy Outlook 2010", Table 8.2. ``Cost and Performance Characteristics of New Electricity Generating Technologies" so fuel costs are over 90% of the marginal cost of nuclear power.

Under cost-of-service regulation, rates are set to allow utilities to recover their recurring operating expenses as well as earn a rate of return on all capital investments in generating equipment as long as that equipment is "used and useful" (F.P.C. vs. Hope Natural Gas Co., 320 U.S. 591, 1944). This creates very little incentive for companies to operate their plants, including their nuclear reactors, efficiently because they receive this compensation regardless of the level of performance. Poor operating efficiency at a utility's nuclear plant means that it must operate other higher-cost generating equipment more. Rates are then adjusted, however, to reflect these higher operating costs making the regulated utility essentially indifferent between the generating facilities in its portfolio. While in theory a regulator could disallow costs for a utility with poor nuclear operating efficiency, this rarely happens in practice. Nuclear power production is highly idiosyncratic and all plants occasionally have problems that lead to suboptimal operating efficiency. Knowing which problems are due to bad luck and which are due to poor management is a challenging, unwelcome job for a utility commission, particularly because safety is often an important consideration in operating decisions and utility commissions do not want to be perceived as taking actions that could jeopardize safety.

In the 1980s and early 1990s a number of states implemented some form of incentive regulation.[9] Recognizing that traditional cost-of-service regulation provides little incentive for cost-minimization, these policies varied from state to state but in all cases were designed to create incentives for firms to increase efficiency, cut costs, and make prudent investments in capacity. Some states implemented incentive programs tied to the operation of particular plants, including nuclear plants. For example, beginning in 1988 Pacific Gas and Electric Company, the owner of the Diablo Canyon nuclear plant in California, was paid a fixed rate for every kilowatt hour of electricity the plant produced. This created an incentive to increase plant efficiency and indeed the plant's capacity factor increased substantially after the plan was implemented. In other states, incentive regulation was less precisely linked to particular plants, but, for instance, allowed the utility to earn a higher rate of return if it maintained a pre-specified average availability across all of its plants. At the end of 1990, sixty nuclear reactors, operating in sixteen states were subject to some form of incentive regulation (Verma, Mitnick and Marcus, 1999). Empirical work at the time

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[9] Knittel (2002) studies the impact of incentive regulation in the U.S. electricity industry on fossil-fuel-powered generating plants.

found that the incentive programs had mixed success at raising average capacity factors at nuclear plants.

In part as a response to the limitations of incentive regulation, several states began to deregulate their electricity markets beginning in the late 1990s. See White (1996) and Joskow (1997) for overviews of the deregulation process. In most states, the deregulation process separated electricity generation, which most economists believe is potentially competitive, from transmission and distribution. Wholesale electricity markets were established in several different regions, and these markets facilitated the growth of independent (nonutility) power producers. Regulators also strongly encouraged utilities to sell all or part of their existing electric generating portfolios.

Divestitures fulfilled several goals. First, they helped jumpstart the nascent nonutility sector. Specifically, many were concerned that vertically integrated companies could distort the wholesale markets, as they would serve as sellers into the markets, owners of the transmission grid to which any nonutility would need access in order to sell and the primary purchaser from the market. Vertical separation alleviated these concerns. Also, the proceeds from the divestitures reimbursed the utilities for any unrecovered costs, thereby avoiding the "stranded cost" problem. Divestitures peaked between 1998 and 2002, during which over 300 electric generating plants were sold and reclassified as independent power producers. Divestitures continued at a slower pace 2003-2010 and by the end of the decade 35% of U.S. electricity capacity was controlled by independent power producers.[10]

The timing of the nuclear plant divestitures followed the broader industry trend and nuclear plants were sold in all but one of the states where regulators instigated divestitures. The one exception is California, which we discuss in detail in Section 4.3. By as late as the end of 1998, all U.S. nuclear reactors were still owned by traditional electric utilities. Then between 1999 and 2002, a total of 36 reactors were divested and reclassified as independent power producers. An additional 12 reactors were divested between 2004 and 2007. See Appendix Table 1 for a complete list of divestitures.

A number of empirical papers have evaluated the effects of U.S. electricity restructuring, including the impact on the efficiency of the wholesale power markets (Borenstein, Bushnell and Wolak, 2000; Bushnell, Mansur and Saravia, 2008; and Hortacsu

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[10] Table 1.1 in U.S. Department of Energy, Energy Information Administration, ``Electric Power Annual'', DOE/EIA-0226, revised April 2011.

and Puller, 2008), consumer responses to retail competition (Hortacsu, Madanizadeh and Puller, 2011) and improvements in inter-regional cost-minimization across power plants (Mansur and White, 2010). Several closely related studies examine the effects of electricity restructuring on plant operations, although much of the existing work has focused on electricity production from fossil-fuel plants. See, e.g., Wolfram (2004), Bushnell and Wolfram (2005), Fabrizio, Rose, and Wolfram (2007), and Craig and Savage (2011).

Nuclear power has received less attention. Zhang (2007) examines the impact of electricity restructuring on nuclear plant operating efficiency during the period 1992-1998, prior to the beginning of plant divestitures. Our analysis adds 10+ years of additional data from the key period *after* the divestitures and consolidation, as well as 20+ years of data from before 1992. Both Fabrizio, Rose, and Wolfram (2007) and Zhang (2007) restrict their analyses to the period before divestitures as both studies use data on plant inputs and output from the Federal Energy Regulatory Commission's (FERC) Form 1, which is completed by electric utilities but is not completed by independent power producers. Fortunately, there are other sources of operating efficiency data for U.S. nuclear reactors. Because the safety of nuclear reactor operations are subject to heavy regulatory scrutiny, all nuclear plants including independent power producers are required to report monthly reactor status to the Department of Energy as well as *daily* reactor status from the NRC. This information available for all plants and years, and is available for each individual reactor inside multi-reactor plants, unlike the information available from FERC.[11]

3 Data Description

This study is conducted using the most comprehensive dataset ever compiled on the operating efficiency of U.S. nuclear power reactors. An advantage of studying nuclear power is that it is highly monitored and nuclear reactor operators are required to report a variety of operating metrics to two different governmental entities. Our data describe forty years of monthly operating efficiency for the universe of U.S. nuclear power reactors. This long panel is important because it allows us to use a variety of different approaches for addressing possible concerns about selection and pre-existing trends. We also put considerable effort

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[11] This distinction is important because in the United States it is common for reactors in multi-reactor plants to be very different. For example, the Millstone nuclear power plant in Connecticut has two reactors that were completed nine years apart (1975 and 1986), of different design capacities (870 and 1156 megawatts), and made by different manufacturers (Combustion Engineering and Westinghouse).

into constructing detailed histories of the companies that own and operate nuclear reactors – information that we use to construct our measures of divestiture and consolidation.

The primary dataset is a 40-year monthly panel that we constructed using data from the U.S. Department of Energy's *Power Plant Report* (EIA-923).[12] The *Power Plant Report* is a monthly survey of operators of nuclear reactors and other large electric generating facilities that includes total monthly electricity generation and other information.[13] The *Power Plant Report* provides a complete record of monthly generation for all reactors from 1970 to 2009. Of the 103 reactors used in our analysis, only two began commercial operation prior to 1970 so the dataset includes the entire operating history for all but two reactors.[14] Reactor outages are recorded as zeros. There are no missing observations.

During the relevant period there is very little entry or exit of nuclear reactors. This simplifies the analysis considerably because it mitigates concerns about selection bias that have been an important issue in analyses of deregulation in other markets (e.g. Olley and Pakes 1996). We include in the main analysis all U.S. nuclear power reactors that were operating as of January 1, 2000. This excludes a small number of reactors that were closed during the 1990s including Millstone 1 and San Onofre 1. No nuclear reactors have been closed in the United States since 1998. As of 2011 there are 104 operating nuclear reactors in the United States. We have 103 in our panel because we have excluded Browns Ferry 1 which was closed for more than two decades between 1985 and 2007.

A commonly reported measure of nuclear reactor operating efficiency is the capacity factor,

$$\frac{net\ generation\ (in\ MWh)}{maximum\ potential\ generation\ (in\ MW) * number\ of\ hours} * 100. \qquad (1)$$

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[12] Previous versions of the EIA-923 were the EIA-906 and EIA-759.

[13] Reactor operators report monthly net electricity generation in megawatt hours (MWh). With electricity generation there is a distinction between gross generation and net generation, where net generation accounts for the electricity consumed by the plant itself and therefore can be negative during shutdowns. Power plants are supposed to report net generation rather than gross generation, but the presence of many exact zeros, particularly during the 1970s and 1980s suggests that at least some plants during some years were reporting gross generation instead. Fortunately in practice the difference is negligible for nuclear power plants because on-site electricity consumption averages less than 1% of total electric generation.

[14] During 1970-1985 and 2001-2002, generation in the *Power Plant Report* is reported at the plant level but not reported separately for individual reactors within multi-reactor plants. Of the 65 plants in our sample, 29 have one reactor, 33 have two reactors and 2 plants have three reactors (Oconee and Palo Verde). During these years for multi-reactor plants we impute reactor-level measures of generation by assigning plant-level generation to each reactor proportionately to each reactor's capacity. In order to assess whether this averaging has introduced any form of bias into our results, later in the paper we re-estimate the model at the plant level and results are very similar.

Capacity factor is calculated as the ratio of actually generated power and maximum potential generation. Usually reported in percent as it is here, the capacity factor is a convenient summary measure of efficiency that is easily interpretable and facilitates comparisons of efficiency across reactors of different sizes.

For our baseline estimates we use a closely related measure,

$$\frac{net\ generation\ (in\ MWh)}{reactor\ design\ capacity\ (in\ MW) * number\ of\ hours} * 100. \qquad (2)$$

When reactor design capacity is equal to maximum potential generation these two measures are identical. The important difference is that reactor design capacity does not change over time whereas maximum potential generation may change over the lifetime of a reactor. Consequently, the latter measure reflects both the *intensity* with which the reactor is used and *changes* over time in maximum potential generation. Whereas capacity factor never exceeds 100, our measure can exceed 100 for a reactor that on average during a period operates at a level of generation above the reactor design capacity. Later in the paper we examine these two components separately, but for the baseline estimates it is valuable to have a single measure.[15] Reactor design capacity comes from U.S. Department of Energy, Energy Information Administration, *Nuclear Power Generation and Fuel Cycle Report 1997*, "Appendix C: Nuclear Units Ordered in the United States, 1953-1996."

The *Power Plant Report* also reports information about reactor operators including whether the reactor operator is a utility or a nonutility. We use this information to construct our measure of deregulation, 1[*Divested*], an indicator variable for reactors that have been sold and reclassified as nonutilities. We identify divestitures in the *Power Plant Report* as the first month in which a reactor changes its status from utility to nonutility.[16] These same data were also used to describe industry consolidation. For each reactor and month

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[15] For our baseline estimates we might have alternatively used net generation itself (without this scaling) or net generation in logs. We prefer the scaled measure to net generation without scaling because U.S. reactors vary widely in design capacity. Net generation in logs would help address this issue, but is not well suited to our application because we have a large number of zeros and negative numbers for net generation.

[16] See Appendix Table 1 for the complete list of divestitures. Because this variable is central for our analysis we put considerable effort into cross-checking divestiture dates against alternative sources. Our primary alternative source of divestiture dates is the U.S. Department of Energy, Energy Information Administration, *Electric Power Monthly*, which in March issues between 2000 and 2003 includes a table ``Electric Utility Plants That Have Been Sold and Reclassified" listing generating facilities that have been reclassified as nonutilities. For the years in which *Electric Power Monthly* is not available we cross-checked the divestiture dates against SEC filings from the companies involved in the transaction. In the vast majority of cases the different sources report the same divestiture date. For a small number of cases in which there were minor discrepancies in divestiture dates between the different sources we rely on SEC filings. Also in some cases the *Power Plant Report* identifies the year but not the month of divestiture and we have used the alternative sources to determine the exact month.

observation we calculate the number of other reactors operated by that reactor's operator.[17] In cases where companies are subsidiaries of other companies we treat this as the same company. Where this is unclear we used SEC filings to determine the ownership structure.[18] Much, but not all, of the variation in consolidation is driven by divestitures so our careful treatment of the divestiture dates and operator changes helps ensure the accuracy of this measure. Before divestitures the mean of our consolidation measure is less than three. Consolidation increases substantially after the period of divestitures and by 2009 the mean of our measure exceeds six.

The second source of data for reactor operating efficiency is the U.S. NRC's *Power Reactor Status Reports*. These data are available for a shorter time period 1999-2009, but are available daily compared to monthly for the *Power Plant Report*. With higher frequency data, we can evaluate reactor outages with considerably more detail. Reactors are required to submit daily reports to the NRC describing capacity factor in percent. Reactors reporting less than 100% provide a brief explanation and reactors that are completely shutdown report whether the outages was due to a manual shutdown (e.g. refueling or maintenance) or an automatic shutdown, also known as a "scram. " The daily data are a complete panel with no missing observations during this 11 year period; a total of 4,017 total days.

We augment the *Power Plant Report* and *Power Reactor Status Reports* with time-invariant reactor characteristics including reactor type, reactor manufacturer, and the date that each reactor began commercial operation from the *NRC Information Digest 2010-2011* (NUREG-1350, Volume 22), published August 2010, Appendix A "U.S. Commercial Power Reactors."

Table 1 provides descriptive statistics. Panel A reports reactor characteristics. Reactor openings peaked during the 1970s and 1980s and most reactors had been operating for at least 10 years when divestitures began in 1999. The descriptive statistics show that U.S. reactors consist of two different reactor types produced by four different reactor

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[17] The *Power Plant Report* elicits information about reactor "operators" rather than "owners". For most reactors there is no distinction between the two. However, there are few reactors with multiple owners. In these cases typically the reactor is operated by the majority owner. There are also a small number of cases in which reactor owners signed operating contracts with outside companies.

[18] One complication is that AmerGen, at the time of some of the divestitures was 50% owned by Exelon and 50% owned by British Energy. In the baseline specification we treat these reactors as being wholly owned by Exelon. Results are essentially identical when we alternatively calculate consolidation for these reactor-month observations by multiplying by .50 the number of reactors owned by each of the co-owners. The simple correlation between the two consolidation measures exceeds .99.

manufacturers. In our sample General Electric produced only boiling water reactors and the other three companies produced only pressurized water reactors. Later in the paper we test to see whether operating efficiency differs systematically across these different designs.

Panel B describes operating efficiency and outages. Mean net generation as a percent of design capacity increases substantially over our sample period from 61% during the 1970s to 92% during the 2000s. The daily reactor status data from the NRC reveals that reactors tend to operate either at full capacity or not at all. In our sample, 77% of all daily observations are 100% capacity factor and 9% are 0% capacity factor. It is relatively common for reactors to operate between 90% and 99% but capacity factors between 1% and 89% are less common and usually indicate a reactor that is ramping up or ramping down, rather than a reactor that is permanently operating at an intermediate power level. For 45% of all observations between 1% and 89% we find that there is a reactor shutdown within 7 days, compared to 23% for reactors operating 90-99%, and only 5% for reactors operating at 100%.

Finally, the table describes reactor outages over the period 1999-2009. By far the most common explanation for reactor outages is refueling. Here we have defined refueling outages as any outage in which refueling was occurring, regardless of whether or not other forms of maintenance were occurring at the same time. A smaller fraction of shutdowns are for maintenance not related to refueling. Finally, about 2% of shutdown-days were due to an automatic shutdown triggered by one of the reactor's safety systems. Also known as "scrams", this is when an operating nuclear reactor is shut down suddenly by rapid insertion of control rods, typically as a result of equipment or operator error. Whereas planned outages begin with a gradual decrease in power levels over several days, scrams shut down a reactor rapidly, putting great stress on plant equipment. There are a total of 831 scrams in our data, or 0.73 scrams per reactor year.

4 Empirical Strategy

4.1 Graphical Analysis

Figure 1 plots net generation as a percent of design capacity by year for reactors that were divested compared to all other reactors. The figure also plots on a different scale the number of operating reactors by year. Early in the sample there were few operating reactors but by the 1990s all of the reactors in the sample are online. Net generation increases steadily throughout the forty-year period, from near 50% of reactor capacity to above 90%. This industry-wide increase is usually attributed primarily to learning-by-doing (Joskow and Rozanski, 1979, Lester and McCabe 1993). "For a complicated piece of equipment like a nuclear power plant this type of learning includes the identification and correction of particular technical `bugs' as well as increasing the ability of workers to use and maintain the equipment more effectively" (Joskow and Rozanski, 1979). Worldwide, nuclear plant output has followed a similar upward trajectory through the 1980s and 1990s.[19] Every piece of equipment in a nuclear reactor has now been studied for decades and inventive engineers have continued to find technical refinements, improvements, and adaptations that increase both output and reliability.

For most of the sample the mean efficiency for divested reactors tracks reasonably closely the mean efficiency for all other reactors. During the 1980s and 1990s the mean efficiency for divested reactors tends to be somewhat lower than the mean efficiency for all other reactors. Then beginning in the late 1990s, the mean efficiency for divested reactors increases sharply and continues to increase during the 2000s. For every year between 2003 and 2009 the mean efficiency for divested reactors is higher than the mean efficiency for all other reactors. This period of increased mean efficiency corresponds with the years after which most divestitures had occurred. Although it is impossible to make definitive statements based on this time series, the pattern is consistent with a causal relationship between deregulation and operating efficiency with a group of reactors that were perennial underachievers converted almost immediately into a group of reactors that consistently outperform the rest of the industry. In the following subsections we turn to a regression framework that allows us to examine the relationship between divestiture, consolidation, and efficiency while controlling for a number of potentially important confounding factors.

It is also worth highlighting the pronounced dip in efficiency during the late 1990s among reactors that were subsequently divested. We have examined this period carefully and this dip in efficiency can be explained by several extended outages. During 1996, 1997, and 1998, ten reactors experience 12+ month outages – seven of which were reactors that were subsequently divested.[20] In Section 5.4 we discuss potential concerns about selection

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[19] World Nuclear Association, "Optimized Capacity: Global Trends and Issues", undated.

[20] In 1995 President Bill Clinton appointed Shirley Jackson to serve as the chair of the NRC. As part of a new

bias and show that the results are similar in alternative specifications that exclude these long outages. One might have been concerned, in particular, that operators overhauled these reactors during the outages which would potentially have led to improved long-run operating efficiency even in the absence of divestiture. We show in Section 5.4, however, that the results are similar excluding reactors that experienced long outages in 1996-1998. Although it is reassuring that our estimates are similar in these alternative specifications, for the main results it is important to include all observations including these periods of unusually poor operating efficiency. Divestiture makes plant operators acutely aware of the financial cost of outages. Extended outages, in particular, are disastrous for independent power producers, so they have incentive to go to great lengths to reduce their probability.

Finally, the figure also brings to mind the possibility of learning spillovers from divested to non-divested reactors. It seems at least plausible that part of the potential gains from deregulation and consolidation would come in the form of learning about best practices, knowledge that at least in theory might quickly spread to regulated utilities. To the extent that these spillovers are important, our estimates of the effect of deregulation and consolidation are going to be biased downward. It is interesting to note, however, that while operating efficiency steadily increased during the 2000s among divested reactors, it was essentially flat at all other reactors. The companies such as Exelon that have made a business out of buying nuclear reactors claim that their operating success is difficult to duplicate, and this lack of recent improvement among non-divested reactors may provide some empirical support for that argument.[21]

4.2 Covariate Balance

The regression analysis described in the following sections is based on comparisons between divested and non-divested reactors, with the operating efficiency of non-divested reactors providing a counterfactual for what would have occurred among divested reactors

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reactor oversight program developed by Jackson, NRC inspectors identified dozens of problems at several different reactors culminating in the long outages observed during this period. Public concern about nuclear safety also peaked during this period following a March 1996 *Time Magazine* cover story, "Nuclear Warriors", March 4, 1996 by Eric Pooley and subsequent Senate investigation (see U.S. General Accounting Office, "Nuclear Regulation: Preventing Problem Plants Requires More Effective NRC Action", GAO/RCED-97-145, May 1997).

[21] In testimony from Exelon before the New Jersey Board of Public Utilities in 2005 the company argued, "A person does not become a great baseball player simply by reading best hitting and fielding practices, people do not become great business leaders simply by reading a book on best practices, and you certainly cannot run nuclear power plants just by reading procedures."

during the 2000s had they not been divested. Whether or not this counterfactual is reasonable depends on whether the groups are *ex ante* similar, in terms of both observable and unobservable characteristics. Formal tests of unobserved characteristics are impossible but studies have argued that research designs that balance observable characteristics suffer less from omitted variables bias (Altonji, Elder, and Tamer 2005). In addition, when observable characteristics are similar between groups the exact functional form for the estimating equation becomes less important.

As a starting point, Table 2 compares mean characteristics for both groups along with *p*-values from tests that the means are equal. Most characteristics are similar in the two groups. Reactor capacity and age, for example, are very similar. The number of reactors operated by the same reactor operator (our measure of consolidation) is similar, and the mean original construction cost is about the same in both groups. For none of the first four characteristics is the difference in means statistically significant.

The table also reports reactor types (pressurized water reactors and boiling water reactors), manufacturer, and location. The proportion of types and manufacturers differs between the two groups, but both groups include reactors of both types and from all four reactor manufacturers. The most striking difference between the two groups, however, is where the reactors are located. The divested reactors are primarily in the Northeast and Midwest, whereas two-thirds of the non-divested reactors are in the South. These differences reflect the geographic pattern of where electricity deregulation occurred in the United States. The empirical challenge in the sections that follow is to construct an accurate counterfactual for how reactor efficiency would have evolved in divested reactors in the absence of deregulation. As we explain in the following subsection, the core of our strategy is to emphasize changes in efficiency over time rather than cross-sectional comparisons between divested and non-divested reactors, allowing us to control for observable and unobservable characteristics of reactors..

4.3 Estimating Equation

This section describes the estimating equation used for our baseline estimates of the effect of divestiture on reactor operating efficiency. The approach is described by the following regression equation,

$$Y_{\text{it}} = \beta_0 + \beta_1 1[Divested]_{\text{it}} + \beta_2 X_{it} + \delta_{\text{i}} + \omega_{\text{t}} + \varepsilon_{\text{it}}. \qquad (3)$$

Here i indexes reactors and t indexes months and in the baseline specification we include all reactor-month observations from the period 1970-2009, over 36,000 total observations. The dependent variable Y_{it} is net generation as a percent of design capacity. Because the dependent variable is measured in percent all coefficient estimates should be interpreted as percentage points. The covariate of interest is $1[Divested]_{\text{it}}$, an indicator variable for reactors that have been sold and reclassified as non-utilities. The coefficient of interest β_1 is the effect of divestiture on efficiency in percentage points. A positive coefficient provides evidence that, everything else equal, divested reactors have better operating efficiency than they would have achieved absent the divestiture.

We report results from specifications that include a range of different control variables. In the full specification we control for a cubic in reactor age (X_{it})[22], reactor fixed effects (δ_{i}), and month fixed effects (ω_{t}) for all 480 months in the sample. The reactor fixed effects play an important role in the regression, controlling for observed and unobserved physical characteristics such as size, reactor type, reactor manufacturer, cooling technology and other factors. The month fixed effects are also important, particularly given the pronounced upward trend in efficiency throughout almost the entire sample period observed in Figure 1. Finally, the error term ε_{it} captures unobserved differences in efficiency across reactor-months.[23] In all results we cluster standard errors at the plant level allowing for arbitrary correlation over time and across reactors in multi-reactor plants.

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[22] Joskow and Rozanski (1979) discuss two mechanisms by which reactor efficiency would tend to increase with age. First, there may be problems with the reactor as initially constructed (e.g. improperly installed equipment) that must be corrected. Second, there may be reactor-specific learning-by-doing by which operations and maintenance personnel become progressively more effective as they understand the idiosyncrasies of a particular reactor.

[23] Our least-squares estimates describe the conditional mean of Y_{it} for a set of explanatory variables. An alternative would have been to estimate a stochastic frontier production function describing the *maximum* amount of output obtainable from a given input bundle (see Aigner and Chu, 1968 and Aigner, Lovell and Schmidt, 1977). The disadvantage of this approach is that it requires one to make parametric assumptions about the error term. To examine the robustness of our results, in alternative results not reported we estimated

Unbiased estimation of β_1 using least-squares requires that the error term ($\varepsilon_{\mathrm{it}}$) is uncorrelated with $1[Divested]_{\mathrm{it}}$ conditional on the available covariates. Our preferred specification includes reactor fixed effects so underlying time-invariant differences between divested and non-divested reactors would not bias the results. However, the orthogonality condition could be violated if divestitures are correlated with trends in reactor efficiency. For example, if the reactors being divested are systematically those with more positive trends in efficiency this would bias upwards the estimates of β_1. We return to this issue in Section 5.4 and discuss several institutional details which provide reassurance that the divested reactors were not selected based on trends in operating efficiency or on the likelihood that particular reactors could be improved after market restructuring.

4.4 Comparing our Estimating Equation with Previous Studies

Several existing studies estimate production or cost functions with data from power plants. See, for example, Christensen and Greene (1976), Kleit and Terrell (2001) and Knittel (2002).[24] Papers that specify a production function estimate the relationship between output, usually measured as annual kilowatt-hours produced, and inputs, usually including capital, labor, fuel, and, occasionally, materials. Cost function papers estimate the relationship between costs, input prices and output. These papers typically use cross-sectional data on fossil-fuel plants, and impose a functional form on the production or cost function, such as Cobb-Douglas or translog.[25]

Although equation (3) is not a production function, we interpret the coefficient on $1[Divested]_{\mathrm{it}}$, the variable of interest, as a measure of efficiency gains. Our dependent variable, net generation scaled by design capacity, is a measure of output much like what has been used in previous studies that estimate production functions. Where our estimation equation differs from previous work is that we do not explicitly include inputs. As discussed

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equation (3) using a stochastic frontier model with a composite error term composed of an inefficiency term assumed to be half-normal bounded above by zero and a normally-distributed idiosyncratic term. With this alternative model the estimated coefficient for $1[Divested]_{\mathrm{it}}$ is similar but somewhat smaller than the baseline estimates presented later in the paper.

[24] In related work, Bushnell and Wolfram (2005) and Fabrizio, Rose and Wolfram (2007) estimate factor-demand equations, derived from production function.

[25] Fabrizio, Rose and Wolfram (2007) describe how certain functional form assumptions may not be appropriate for power plants and specify a production function which is Leontief in fuel inputs plus capital, labor, and materials. They derive factor demand equations for labor, materials and fuel, and hold capital fixed with plant fixed effects.

in Section 2, by far the most important input for nuclear power production is the capital embodied in the plant itself. Construction costs represent almost 80% of the total cost of nuclear power, compared to, for example, only 15% for natural gas plants (Joskow and Parsons, 2009). Our preferred specifications include reactor fixed effects, which control for time-invariant differences in capital inputs across reactors. Also, month fixed effects control for industry-wide changes in nuclear production (e.g., due to increased automation, or changes due to NRC regulations). Thus while we do not explicitly model reactor output as a function of inputs, these fixed effects control for the important variation in inputs, implying that the divestiture-related changes we estimate reflect efficiency improvements. In particular, the coefficient on $1[Divested]_{\mathrm{it}}$ in (3) measures how far the utility owners were from the production frontier, which is defined by the production of the nonutility owners.

Our interpretation is bolstered by several additional institutional details on other inputs. Note that while we can control for the original capital invested in the reactor and industry-wide trends, it is possible that the divestitures changed factor prices for more variable inputs in a way that allowed the new operators to produce more output. Under this alternative interpretation, utility and nonutility plants are both on the production frontier, but they face different input prices and so produce different output levels. In other words, both utility and nonutility operators could be producing at a point of tangency between the budget constraint and production frontier, but lower factor prices could loosen the budget constraint for nonutility owners.[26]

We do not think that is the case. First consider labor inputs. Existing evidence on fossil-fuel plants suggests that, contrary to that line of reasoning, nonutility operators reduced staffing levels (Shanefelter 2010). While the same plant-level employment data are not available for nuclear plants, we were able to obtain two years of post-divestiture data from the EIA (2001 and 2002). We matched this to information on average annual employment from the FERC Form 1 pre-divestiture. We do not have a large enough sample to perform a rigorous statistical analysis, but at the six divested plants that we can follow from the late 1990s to 2002, average employment dropped by 18 percent. At the 24 utility plants, average employment only dropped by about 6.5 percent.

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[26] For example, previous work has shown that utilities are more likely to employ unionized workers and pay higher wages (Rose, 1987). One might conjecture that nonutility operators could undo existing labor contracts, reduce the price of labor, and hire more workers, who could help the plants produce more output.

If anything, therefore, by not including labor inputs in equation (3) we are underestimating the efficiency gains from divestitures. Labor input costs are a small share of the overall cost of nuclear power production, so this omission is not material to our results. Specifically, while available data from the Bureau of Labor Statistics is insufficiently detailed to examine changes in employment associated with nuclear divestitures directly, the national-level data provide a good indication of the importance of labor in this sector.[27] In 2009, the industry employed 62,000 workers at a total cost of $6.4 billion (approximately $103,000 annually per worker in wages, including bonuses). The plants in our sample employed roughly 800 workers per year, so if divested owners reduced their wage bill by 15% more than utility, they would save roughly $12 million dollars. As there are on average two reactors per plant, this aggregates up to less than $300 million in savings across all of the divested reactors. Although substantial, this is small compared to the approximately $2.5 billion in additional revenue from increased output.

In addition to labor inputs, it is possible that the divested firms invested more capital in the plants. The reactor-fixed effects only control for the initial capital investment, not subsequent upgrades. It is certainly plausible that the nonutility owners made capital upgrades to the plants they acquired, and we provide evidence below that shows plant capacity expanded after divestitures. It is hard to reconcile this with optimizing behavior on the part of the utilities. As described in the case of labor, increased production on the part of the nonutility owners would be consistent with an outward rotation of the firm's budget constraint if non-utilities faced lower capital costs. Dating back to Averch and Johnson (1962), however, theory and empirical evidence suggests that cost-of-service regulation reduces capital costs for utilities.

Plant-level data are not available on uranium consumption so it is not possible to examine directly whether divested reactors are more efficient at converting enriched uranium into electricity. Although this would have been interesting, aggregate data suggest that uranium fuel consumption is approximately proportional to electricity generation.[28]

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[27] The Quarterly Census of Employment and Wages reports state and national information about employment and wages by NAICS code. Nuclear power generation has its own NAICS code (221113) but the Bureau of Labor Statistics withholds publication of data for any geographic industry level in which there are fewer than three firms, effectively preventing these data from being disclosed at the state-level for the nuclear industry.

[28] According to U.S. Department of Energy, Energy Information Administration, "Uranium Marketing Annual Report", August 2010, the amount of uranium loaded into U.S. nuclear power reactors increased 22% from 40.4 million pounds in 1994 to 49.4 million pounds in 2009. During the same period according to U.S. Department of Energy, Annual Energy Review 2009, "Table 9.2 Nuclear Power Plant Operations" nuclear electricity net generation increased 25% from 640.4 billion kilowatt hours to 798.7 billion kilowatt hours.

Moreover, fuel costs are a relatively small share of the total cost of nuclear power production. This limits the magnitude of any potential changes in efficiency along this margin and means that the level of uranium prices is irrelevant to optimal operating decisions. During most periods wholesale electricity prices are much higher than the marginal cost of nuclear power. And, even though there are occasional hours for which electricity prices fall below marginal cost, the long ramp periods for nuclear reactors mean that it is impossible for reactors to cost-effectively reduce supply during these periods. These facts suggest that as long as the reactor is available (i.e., not in an outage), the operator should procure fuel to generate as much electricity as possible. More precisely, we are assuming that there is no substitution between nuclear fuel and other inputs. Nuclear reactor production is Leontief in the availability of the plant (Y^{Avl}), which is a function of capital and labor, and fuel (F): $Y^{Act} = \min(Y^{Avl}(K,L),F)$. Marginal fuel costs are so low, however, that the fuel constraint is never binding and $Y^{Act} = Y^{Avl}$. Since Y^{Act} is the dependent variable in equation (3), $1[Divested]_{\mathrm{it}}$ measures changes in the efficiency of producing availability and is not a function of fuel inputs.

5 Main Results

5.1 The Effect of Divestiture on Reactor Efficiency

Table 3 reports baseline estimates of the effect of divestiture on nuclear reactor operating efficiency. Estimated coefficients and standard errors corresponding to $1[Divested]_{\mathrm{it}}$ are reported from five separate regressions. The dependent variable in all regressions is net generation as a percent of design capacity (equation 2). Controlling only for month fixed effects in column (1), divestiture is associated with a 6.5 percentage point increase in efficiency. As the mean of scaled net generation in our sample for non-divested plants in 2000 was 87%, the increase in divestiture is equivalent to an increase to approximately 94%. The coefficient is statistically significant with a *p-value* less than 0.001.

Column (2) adds reactor fixed effects and the coefficient increases to 10.4. This increase reflects the fact that the divested reactors tended to underperform relative to other reactors during the extended pre-period, as can be seen in Figure 1. Columns (3), (4), and (5) add reactor age, weight observations by reactor capacity, and collapse the dataset to the plant level, respectively, and the results are similar. Even with the full set of control variables the R^2 from these regressions is reasonably low. As we show in detail later in the paper, most of the variation in efficiency comes from reactor outages rather than changes in efficiency along the intensive margin. The low R^2 reflects the fact that it is relatively difficult to predict the timing of outages.

This is a *substantial* increase in efficiency. In the United States, nuclear power is a $40 billion dollar annual market, accounting for 20% of total electricity production.[29] In 2009, independent power producers in the United States owned 46,649 megawatts of nuclear capacity, so a 10.2 percentage point increase in efficiency implies 42 billion kilowatt hours of additional electricity production.[30] This is $2.5 billion dollars worth of power annually, almost enough power to meet electricity demand for all the households in New England.[31]

Moreover, this increase in efficiency is large enough to have substantial implications for the environment. Based on average emission levels from the U.S. electricity sector, the increase in operating efficiency associated with divestiture implies an annual decrease of 38 million metric tons of carbon dioxide emissions.[32] Using a conservative estimate for the social cost of carbon dioxide ($20 per ton) this implies an additional $760 million in benefits annually.[33] To put this into perspective, we are finding that the *increase* in

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[29] According to U.S. Department of Energy, Energy Information Administration, "Annual Energy Review 2009", released August 2010, Table 8.2a "Electricity Net Generation", nuclear plants in 2009 produced 799 out of 3,953 billion kilowatt hours of electricity produced in the United States. In calculating the size of the nuclear power market we assumed an average wholesale price of $60 per megawatt hour.

[30] U.S. nuclear capacity by producer type is described in U.S. Department of Energy, Energy Information Administration, "Annual Energy Review 2009", released August 2010, Table 1.1 "Existing New Summer Capacity". A 10.2 percentage point increase in net generation is (.102)(46,649)(24 hours/day)(365 days/year)(1000 kilowatts/megawatt) = 42 billion kilowatt hours.

[31] This calculation assumes an average wholesale price of $60 per megawatt hour. U.S. Department of Energy, Energy Information Administration, "Wholesale Market Data from Intercontinental Exchange" reports daily average wholesale prices for six major trading hubs. Over the period 2001-2009 the average wholesale price was $61.00. According to U.S. Department of Energy, Energy Information Administration, "Electric Power Monthly 2010", Table 5.4.B. "Retail Sales of Electricity to Ultimate Customers", residential customers in New England (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) consumed 46 billion kilowatt hours of electricity in 2009.

[32] From U.S. Department of Energy, Energy Information Administration, "Annual Energy Review 2009", released August 2010, Table 12.7a "Emissions from Energy Consumption for Electricity Generation" total carbon dioxide emissions in 2008 for electricity generation were 2.48 billion metric tons. From Table 8.2a "Electricity Net Generation," total electricity generation from fossil fuels was 2.73 trillion kilowatt hours. Thus 42 billion kilowatt hours of fossil fuel-based power implies (2.48)(42)(1,000,000)/(2.73) = 38 million metric tons of carbon dioxide emissions.

[33] Federal Interagency Working Group (2010) presents a range of values for the social cost of carbon dioxide according to different discount rates and for different time periods that is intended to capture changes in net agricultural productivity, human health, property damages from increased flood risk, and other factors. In Table 15A.1.1 with a 3% discount rate (their "central value") for 2010 they find a social cost of carbon dioxide of $21.40 (in 2007 dollars) per metric ton of carbon dioxide. In 2010 dollars this is approximately $22.

electricity production associated with divestiture is more than *all* the electricity produced by U.S. wind and solar generation combined over this period.[34]

These benefits from divestiture must be weighed against several additional costs. The marginal cost of generating power with a nuclear reactor is low, but not zero. Average fuel costs for nuclear power ($7 per MWh) imply an annual increase in fuel expenditures of approximately $300 million.[35] An additional potential cost is labor, though as we described earlier in the paper, the available data suggest that, if anything, the number of workers in divested reactors has actually declined. Another cost is the cost of storing the additional spent uranium fuel. It is difficult to quantify the external costs of this additional spent fuel but available estimates in the literature indicate that the *private* costs of dry cask storage are small.[36] A comprehensive accounting of the costs and benefits of divestiture would need to include these additional costs, as well as additional benefits such as decreased emissions of local pollutants, and, in the long-run, decreased investment in new generating capacity.[37]

5.2 Estimates by Reactor Type, Manufacturer, Vintage, and Month of Year

Table 4 reports estimates from three separate regressions which describe the effect of divestiture by reactor type, manufacturer, and vintage. In each case the indicator variable

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[34] According to U.S. Department of Energy, Energy Information Administration, "Annual Energy Review 2009", released August 2010, Table 8.2a "Electricity Net Generation", during the period 2000-2009 U.S. wind and solar generation combined averaged 26 billion kilowatt hours annually. The average total capacity of divested reactors over the same period is 36,517 megawatts so a 10.2 percentage point increase in net generation is (.102)(36,517)(24 hours/day)(365 days/year)(1000 kilowatts/megawatt) = 32 billion kilowatt hours annually.

[35] MIT (2009) reports fuel costs of $7 per MWh for nuclear power based on fuel prices of $0.67 per million BTU and average heat rates of 10,400 BTU per kilowatt hour. A 42 billion kilowatt hour increase would then imply $294 million annually in additional fuel expenditures.

[36] In the United States there is no federal spent fuel storage facility and no facilities for the reprocessing of spent fuel. Currently, spent fuel is stored on site in storage pools or, increasingly, in dry cask storage. According to U.S. NRC, "Information Digest 2010-2011" NUREG-1350, Volume 22, published August 2010, the total amount of spent fuel in the United States increases by 2,000 tons annually, so a 10% increase in spent fuel from half of the nation's reactors is approximately 100 tons annually. A 2008 report commissioned by the U.S. Department of Energy reports that private lifetime costs for dry cask storage including licensing, construction, procurement, loading, and maintenance are $120 per kilogram which (ignoring any potential economies of scale) implies $11 million in additional costs. See Idaho National Laboratory "Advanced Fuel Cycle Cost Basis", INL/EXT-07-12107, Module E2 "Dry Storage of Spent Nuclear Fuel" for details.

[37] In future work it would also be interesting to examine the *distribution* of these costs and benefits. The environmental impacts accrue globally for carbon dioxide, regionally for criteria pollutants, and locally for changes in storage of spent uranium fuel. The private benefits of operating efficiency, however, are shared primarily between ratepayers and shareholders, with the exact division of gains depending on how electricity prices were impacted. In a perfectly competitive market, increased production from nuclear reactors shifts the supply curve for electricity to the right, replacing higher-cost forms of generation and decreasing average wholesale electricity prices. Exactly how much electricity prices have actually come down is an empirical question that depends on demand- and supply-side factors.

$1[Divested]_{\mathrm{it}}$ is interacted with indicator variables for different reactor categories as listed in the row headings. The estimated coefficients on these interaction terms are positive in all nine cases and statistically significant at the 1% level in eight out of nine cases. In none of the three regressions can one reject the null hypothesis of equal coefficients. The uniformity of these results indicates that the efficiency gains were experienced broadly across reactors of different types, manufacturers, and vintages.

Figure 2 plots point estimates and 95th percentile confidence intervals for a regression that allows the effect of divestiture to differ across calendar months. All twelve coefficient estimates are positive and statistically significant at the 5% level. The largest point estimates are for May and November -- historically the peak months for refueling shutdowns because of the relatively low level of electricity demand. During these months there is more scope for increasing efficiency compared to, for example, the peak summer months when most reactors were running at close to full power even prior to the divestitures.

5.3 The Effect of Consolidation on Reactor Efficiency

The divestitures between 1999 and 2007 transferred operation of many reactors from companies subject to traditional cost-of-service regulation to independent power producers selling power in competitive wholesale markets. At the same time, however, the divestitures consolidated reactor operations among a smaller set of companies. Economists have long recognized the potential efficiency gains from consolidation in the nuclear power industry. Joskow (1982) explains,

> “The way reactors are built and operated must be changed… At present, more than forty utilities have nuclear-power plants operating or under construction. Some of these utilities are very large, while others are very small. It is at least arguable that there are opportunities for economies of scale in the construction and safe operation of nuclear facilities that are not being exploited because of the fragmented ownership pattern that flows from the present structure of the electric-utility industry in the United States.” (page 250)

The divestitures led to an unprecedented level of consolidation in the industry. Figure 3 plots annual means of the number of other reactors operated by the same reactor operator over the period 1970-2009 for divested reactors and all other reactors. As late as the mid-1990s, there was relatively little consolidation in the industry. The average reactor was operated by a company that operated less than three other reactors, and most reactors were operated by companies that operated only one or two other reactors. By the end of 2009, however, reactors were operated by companies that operated an average of more than six other reactors and the three largest companies (Entergy, Exelon, and NextEra) operated about one-third of all nuclear capacity in the United States.

In principle, consolidation could improve operating efficiency in several ways. Whereas a utility with a single reactor may rely on contract employees to perform infrequent tasks, such as refueling outages, which take place on average every eighteen months, a consolidated nuclear company can hire highly skilled employees and train them to appreciate the idiosyncrasies of the company's reactor fleet. A chairman of a major nuclear company explains, "you need to have a significant number of highly qualified staff across all the range of disciplines, and it's more cost-effective to service a number of plants than to service a single plant."[38] Also, within a consolidated company, employees can disseminate best practices for refueling and maintenance.[39] These effects are in addition to incentives created by a divestiture, in which the operator, no matter its size, becomes the residual claimant on any revenues earned from increased efficiency.

It is instructive to consider the variation in our data that will help distinguish a consolidation effect from the divestiture effect. First, there were many changes in operators that were not associated with divestitures but that changed the level of consolidation in the industry. For example, when Toledo Edison, Duquesne Lighting Company, and Centerior were combined to form First Energy in 1997, the four reactors operated by those companies may have experienced improved operations. Second, there are several reactors that are operated by companies that control both divested and cost-of-service regulated, utility reactors. For example, Entergy began as a Southern investor-owned utility and continues to operate reactors in Arkansas, Mississippi, and Louisiana. As of 2009, Entergy

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[38] Robin Jeffrey, deputy chairman of British Energy quoted in "Shut Down: Can Nuclear Plants Survive Deregulation? The Jury is Still Out", *Wall Street Journal*, September 14, 1998. British Energy owns eight nuclear plants in England and Scotland and through a joint venture *Amergen* purchased several plants in the United States including Clinton and Three Mile Island 1.

[39] Anecdotal evidence suggests that this has indeed occurred. Gary Leidich, the president of FirstEnergy Nuclear described the company's acquisition of three nuclear plants as follows. "It was three separate facilities, each pretty much doing their own thing. Now it's a corporate organization with a fleet approach." Quoted in "Executive Vows Strong Focus on Plant Safety" in *The Plain Dealer*, Cleveland Ohio, March 9, 2004. This fleet approach means, for example, that plant operators have a daily 7:30 a.m. conference call for discussing potential problems and managers at FirstEnergy travel from plant to plant.

operates eleven reactors, five of which are located in these Southeastern states which have not restructured their electricity markets. This explains why the pale line in Figure 3, reflecting the average number of reactors operated by operators of non-divested reactors increased after 2000. It is possible that these plants benefited from Entergy's acquisition of the divested plants, through the mechanisms we identified above.

Table 5 reports regression estimates. Column (1) presents the baseline estimate, identical to the third column in Table 3. In column (2), we expand the estimating equation to include our consolidation variable. The coefficient estimate on consolidation is positive, implying that increasing the number of other reactors operated by the same operator improves a reactor's efficiency by .48 percentage points.[40] The range of the consolidation variable is 0 to 16 so the point estimate implies that a change from the minimum to the maximum for this variable would increase efficiency by 7.7 percentage points, an effect about as large as the point estimate on $1[Divested]_{\mathrm{it}}$.

Columns (3) and (4) test whether the gains from consolidation are higher if the other reactors operated by the reactor operator are of the same type (pressurized water reactor versus boiling water reactor) or manufactured by the same firm. The point estimates are similar to the point estimate in column (2) suggesting that the gains from consolidation come from broad changes in operations and maintenance, rather than from specific changes related to the technical characteristics of particular reactor designs.[41] It is difficult to draw strong conclusions, however, because the parameter estimates are imprecisely estimated.

We performed several robustness checks to verify our interpretation of these results. First, while the variation in our data allows us to estimate both a divested and a consolidation effect, the degree of consolidation is certainly higher among divested plants,

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[40] In alternative results not reported we have tested for nonlinear effects by including a square term and by allowing for different bins (0-4, 5-8, 9-12, and 13-16) and in neither case do we find evidence of a nonlinear effect. We also considered an alternative specification which includes an interaction between $1[Divested]_{\mathrm{it}}$ and our measure of consolidation. In this regression the point estimates on both the interacted and uninteracted consolidation terms are positive but neither are statistically significant.

[41] In related work, Lester and McCabe (1993) compare operating efficiency of U.S. and French nuclear reactors. In part because the United States was a pioneer in nuclear power generation, there was a great deal of technological advancement and learning during the period reactors were being built, and consequently there are many different designs, even among reactors by the same manufacturer. In contrast, France adopted a single reactor design (essentially a copy of the Westinghouse pressurized water reactor) and 58 out of 59 French reactors operating as of 2009 are this same type (International Atomic Energy Agency, 2010, "Nuclear Power Reactors of the World", Table 14). Lester and McCabe argue that this standardization has increased learning-by-doing in plant operation and test empirically for differential learning-by-doing among reactors of different designs. These regression specifications can be viewed similarly, as a test of whether inter-reactor learning or economies-of-scale are stronger among reactors of a certain type or made by a particular manufacturer.

as depicted in Figure 3. In column (5) we re-estimate the specification reported in column (2) using only reactors that were never divested and dropping the divestiture indicator variable. The coefficient on the number of reactors controlled by the same operator is larger than the coefficient reported in column (2) and statistically significant (*p*-value=0.016), suggesting that gains from the large divested companies are not biasing the coefficient estimate upward. We also examined whether the consolidation effect varies depending on the mix of utility and nonutility reactors controlled by the operator. For instance, if a company was able to shift resources, such as skilled operators, from the utility to the nonutility plants, utility plants may experience worse efficiency in a more consolidated company. We do not see evidence of this effect, though there are only nine reactors operated by companies with both utility and divested assets, so results are imprecise. Finally, in column (6) we collapse our data to the plant level and estimate spillovers from an operator having an additional plant in its fleet. The effect is nearly twice as large as the estimated effect in the reactor-level regression, reflecting that the typical reactor is housed at a two-reactor plant so that the mean of the consolidation variable in the plant-level specification is about half as large. In the plant-level regression the coefficient on the consolidation variable is highly statistically significant (*p*-value=0.013).[42]

Overall the results provide some mild evidence of broad-based efficiency gains from industry consolidation. The point estimates corresponding to the consolidation measure are only statistically significant in columns (5) and (6) but are consistently positive and large enough to be economically important. Also interesting is that the estimate corresponding to divestiture is consistently large, statistically significant, and reasonably similar across specifications, suggesting that it is divestiture and not consolidation driving the large share of the efficiency gains.

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[42] An interesting question is whether these efficiency gains could have been realized through operating contracts, perhaps with only a few highly consolidated operating companies nationwide. Testimony from Exelon before the New Jersey Board of Public Utilities in 2005 about a proposed merger with PSEG suggests that the answer is no. "The Operating Services Agreement (OSA) does not provide sufficient financial incentive for Exelon to agree to a similar agreement in the absence of the merger. The OSA diverts significant Exelon management attention from other business opportunities… and does not allow Exelon sufficient financial incentive or operational control to bring Salem and Hope Creek performance up to Exelon's fleet-wide performance levels. In short, if it had made business sense for Exelon and PSEG to enter into an OSA in the absence of a merger, than we would have done so a long time ago."

5.4 Considering Possible Concerns about Selection Bias

This subsection evaluates potential concerns about selection bias and differential trends in operating efficiency. From an empirical design perspective, the ideal experiment would be to take the entire population of nuclear reactors and then *randomly* select a subsample of reactors to divest. From the mean characteristics reported in Table 2 is it clear that the recent experience in the U.S. nuclear industry falls short of this ideal. Our preferred specification includes reactor fixed effects which control for observed and unobserved mean differences between reactors. Still, one could be concerned that the reactors that were divested had different pre-existing trends. One possibility, for example, would be that reactors were selected based on which reactors stood the most to gain from restructuring. Although it is impossible to completely rule out these concerns, there are several features about how deregulation occurred in practice that substantially decrease the scope for selection bias in this context.

First, in almost all cases decisions about divestiture were made at the state level, not at the reactor level. In all but one state, either *all* of the state's nuclear reactors were divested or *none* of the state's reactors were divested. The one exception is the state of Michigan, where one reactor was divested but the other three reactors were not. Given that Michigan is an unusual case, we find it reassuring that our results are essentially identical when the four reactors in Michigan are excluded from the sample. See column (1) in Table 6.

Second, almost all nuclear reactors were divested in states where deregulation occurred. The fourteen states that have deregulated their electricity markets (as of 2011) are Connecticut, Delaware, Illinois, Maine, Maryland, Massachusetts, Michigan, New Hampshire, New Jersey, New York, Ohio, Oregon, Pennsylvania, and Texas. With the exception of Michigan, all of the nuclear reactors in all of these states have been divested. An interesting case is California which divested a substantial amount of the fossil-fuel-fired power plants in the late 1990s before suspending deregulation after the California Energy Crisis in 2000. Neither of the state's two nuclear power plants (Diablo Canyon or San Onofre) have been divested, potentially raising concerns about selection. Again, however, we find it reassuring that excluding these reactors from the sample the estimated coefficient is essentially unchanged. See column (2).

Third, in states where electricity deregulation did not occur, nuclear reactors were not divested in almost all cases. Here the two exceptions are Iowa and Wisconsin. These states did not deregulate their electricity markets but have divested a considerable fraction of their generating facilities. Once again, however, when these reactors are dropped from the sample the coefficient estimate corresponding to $1[Divested]_{\mathrm{it}}$ is essentially unchanged. See column (3).

Fourth, most of the divestitures occurred over a relatively short period of time so differential *timing* of divestitures cannot explain the results. Of the 48 reactors that were divested, 36 were divested during a three and a half year period between July 1999 and November 2002. When we re-estimate the model using January 1, 2001 as the divestiture date for all divested reactors, the estimated coefficient on $1[Divested]_{\mathrm{it}}$ is smaller (consistent with attenuation bias), but still positive and statistically significant (7.9 with a t-statistic of 3.31).

Thus there is a strong but not perfect correlation between deregulation and nuclear divestitures. Although this greatly reduces the scope for reactor-by-reactor selection bias, it raises the broader question of whether state-level decisions about whether to deregulate or not were influenced by potential efficiency gains in nuclear reactors, or whether these decisions were driven by some other factor that is correlated with trends in operating efficiency. Again it is impossible to completely rule out these concerns but the existing literature about the determinants of deregulation provides an important point of reference. Deregulation came out of a broader discussion about the electricity market as a whole, including all forms of generation, unbundling transmission and distribution, and introducing retail choice. The idea that competition would create incentives for more efficient operation of nuclear power reactors was only one small piece of this larger discussion. A number of studies have examined the determinants of deregulation and determined that the best predictors are liberal politics and high electricity prices (White 1996). Differences in electricity rates across states has much more to do with the *type* of generating equipment in each states' generation portfolio, rather than the *efficiency* with which it is operated. For example, utilities with access to federally subsidized hydropower typically have lower rates than other utilities. And again, our preferred specification includes reactor fixed effects which control for time-invariant differences across reactors and the states in which they are located.

In practice there is a distinct geographic pattern to deregulation, with most divested reactors in the Northeast and most non-divested reactors in the South. Is there something different about reactor operation in these different regions? For example, could the weather in the Northeast region be more conducive to increasing efficiencies above 90%? The answer is probably not. Outdoor temperature, or more importantly, the temperature of cooling water, does affect electricity production, but within the relevant range of temperatures the effect is too small to matter. Moreover, the daily data show that divested reactors have fewer outages throughout the year, not just during the winter. This finding would be difficult to reconcile with some region-specific climate-driven factor. Finally, when we exclude from the regression all reactors in the Northeast (see column 4 of Table 6), the point estimate is again almost identical. This is a demanding test of the data which requires excluding more than half of the divested reactors from the sample and the fact that the point estimate is again positive and statistically significant at the 1% level provides additional evidence that the observed efficiency gains are not driven by selection.

Finally, the specifications described in columns (5)-(8) are aimed at assessing potential related concerns about long outages during the period 1996-1998 that cause the pronounced “dip” in efficiency in Figure 1. The point estimates drop somewhat in these specifications but remain large and highly statistically significant, providing evidence that the baseline estimates are not driven by these long outages. It is not surprising that point estimates are smaller in these regressions because they exclude periods of unusually poor operating efficiency among divested reactors prior to divestiture. We include the long outages in our main results as they are part of the divestiture effect we seek to measure. Deregulation changes incentives, making reactor operators financially responsible for long outages such as these. For an independent power producer, the financial implications of a 12+ month outage are devastating, and we do not think it is a coincidence that the incidence of outages has decreased substantially among divested reactors. In the following section we turn to daily data on reactor status which allows us to examine these outages explicitly.

6 Understanding the Mechanisms behind Post-Divestiture Gains

6.1 Frequency and Duration of Outages – Graphical Analysis

We next turn to ancillary evidence aimed at understanding the *mechanisms* driving this observed increase in efficiency. We first examine maximum generating capacity. U.S. nuclear power reactors are licensed with the NRC to be able to operate at a particular maximum heat level. However, plant operators can petition to have this maximum thermal capacity increased. This is known as an "uprate".[43] Over this period nuclear uprates have added 6,000 megawatts of total electric capacity -- the equivalent of 6 new 1000 megawatt reactors.

Figure 4 plots mean maximum licensed thermal capacity for divested and non-divested reactors over the period 1970-2009. The sample of reactors here and throughout the analysis in this section is again all reactors that were operating as of January 1, 2000. Capacity is expressed as a percent of the original design. During the early 1970s all reactors operated at their original design capacities. During the late 1970s, 1980s, and 1990s, there were 4, 10, and 33 total uprates, respectively. Uprates increase sharply beginning around 2000, with an additional 81 uprates between 2000 and 2009.[44] Independent power producers have been more likely to perform uprates, though investor-owned utilities have been active as well. In Section 6.2 we turn to a regression analysis with these same data in order to determine whether the difference in uprates is statistically significant after controlling for covariates.

Other possible explanations for the increase in operating efficiency include an increase in operating days or an increased capacity factor when operating. In order to examine these mechanisms we turn to the daily data from the NRC. Whereas the analysis in Section 5 uses *monthly* data for a 40-year period 1970-2009, these *daily* data are available only for 1999-2009. This makes this alternative dataset less useful for the primary empirical exercise in the paper – constructing a counterfactual for how reactor efficiency in

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[43] In a nuclear reactor enriched uranium creates a chain reaction that creates heat that is used to produce electricity. Heat is produced either in the form of super-heated water in a pressurized water reactor or as steam in the case of a boiling water reactor. Nuclear fission is moderated using control rods made of boron or other elements which absorb neutrons, reducing the amount of heat that is generated. Using more highly-enriched uranium or less moderating materials leads to more heat, and more electricity.

[44] Technological advances in fuel rod construction provide part of the explanation for why uprates have become more common since the 1990s. Innovations in metallurgy have increased the thermal capacity of fuel rods, allowing them to run hotter without leaking radioactivity.

divested reactors would have evolved in the absence of divestiture. Nonetheless, the fact that these data are available at a very high frequency makes them particularly valuable for examining reactor outages.

Figure 5 plots the fraction of reactors not operating by day over the period 1999-2009. The figure reveals a pronounced seasonal pattern of outages. Each year outages peak twice, once during the spring and again once in the fall. At the peaks, between 15% and 30% of all reactors in the United States are not operating during a given day. At the troughs, between 0% and 5% of all reactors are not operating. Figure 6 investigates this pattern further, illustrating how the fraction of reactors not operating by day has changed over time. Mean outages are plotted separately for reactors divested 1999-2007 and all other reactors. At the beginning of the sample the annual pattern for both groups is reasonably similar but by the end of the sample outages are considerably less frequent among divested reactors. This holds for almost all days during the entire year, with particularly large differences during the late spring and late fall.

Figures 7 and 8 provide additional evidence about the pattern of outages over time. The first figure plots the mean number of outage days per reactor 1999-2009. Both time series are relatively noisy but it is interesting that mean outages among divested reactors is below mean outages among all other reactors for every year between 2004 and 2009, with some suggestion that the gap may be increasing over time. Figure 8 plots the mean number of scrams per hour of reactor operation. Here there is a substantial and reasonably steady decrease in scrams industry-wide, and little evidence of a divergence between divested and non-divested reactors.

While divested reactors appear to have fewer outages, *during operation* they do not appear to be operating at a higher capacity factor. Figure 9 plots mean capacity factor by day of year for operating reactors. Divested and non-divested reactors follow a very similar pattern, peaking in the winter and summer when almost all reactors are operating at full power. Across all days 2005-2009 mean capacity factor for operating reactors is almost exactly identical for both groups, 97.96 for divested reactors versus 98.02 for non-divested reactors. These high capacity factors reflect the fact that, when operating, nuclear reactors are typically run at full power. A large fraction of the observations of capacity factor that are below 100%, moreover, are from reactors that are ramping down to or out of outages – rather than reactors that are being consistently run below 100%. The seasonal pattern makes sense when interpreted in this context because the somewhat lower capacity factors during spring and fall are during the periods in which outages are more common, and thus a larger fraction of operating reactors are ramping up and down.

6.2 Frequency and Duration of Outages – Regression Analysis

Table 7 provides regression estimates that are roughly analogous to the graphical analysis in the previous subsection. These ancillary regressions continue attempting to tease out the mechanisms driving the increase in efficiency observed in Section 5. Regression estimates are reported for seven different dependent variables including maximum capacity, the frequency, number, and length of reactor outages, and capacity factor while operating. Overall, the regression results are consistent with the basic pattern of behavior observed in the graphical analysis.

Panel (A) examines maximum generating capacity. Regression coefficients are reported for two different measures of capacity and for three different specifications which add control variables as one moves from left to right. In the first row the dependent variable is the maximum observed level of positive net generation over the previous twelve operating months as a percentage of reactor design capacity. Controlling for reactor fixed effects and a cubic in age, divestiture is associated with a 1.7 percent increase, although the coefficient is not statistically significant. The second measure of capacity is licensed maximum thermal capacity. As described above, plant operators can petition to have their maximum thermal capacity increased, and the regression estimates in this row can be seen as a test of whether divested plants were more likely to perform uprates. The coefficient estimates in this row are similar in magnitude to the coefficients in the first row. This suggests that divestiture-related capacity increases were primarily driven by changes in the thermal capacity as opposed to changes in the electrical generating capacity. In the last two rows the estimated coefficients are not statistically significant at conventional levels (*p*-value .09 in both rows).[45]

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[45] One notable feature of Figure 4 is that during the late 1990s the average thermal capacity among subsequently divested reactors appears to lag behind the average thermal capacity for all other reactors. This corresponds with the period of long outages discussed in Section 4.1 and 5.4. The capacity increases among divested reactors do not appear during or immediately after these outages indeed it is not until 2001 and 2002 that the large uprates are observed in Figure 4. As a robustness check, we have also estimated this equation excluding 1995-1998 and the results are almost identical.

Although modest uprates (2-3%) can be performed with little or no equipment replacement, larger uprates typically require modifications to non-nuclear equipment such as high-pressure turbines, condensate extraction pumps, motors, and transformers. The cost of these modifications ranges from $750 to $900 per kilowatt of added capacity.[46] At the top half of this range, a large uprate could cost total in excess of $200 million. Although not negligible, this is small compared to, for example, the cost of building a new nuclear reactor.

Panel (B1) focuses on reactor operating days and shutdowns. The first dependent variable is an indicator variable for whether the reactor is operating. In our sample this is 91% of all reactor-day observations. The estimated coefficients in this row range from 3.5 to 3.9 percent across specifications. This is a large effect relative to the mean, implying that divestiture is associated with a decrease in outages of about one-third, equivalent to an increase of 13-14 operating days per year per reactor. These results are consistent with the graphical analysis above and suggest that this basic pattern of decreased outages holds even after controlling for the different covariates.[47]

Although they represent a small share of total outages, automatic shutdowns or "scrams" are particularly interesting because they have been used in previous studies as a measure of reactor safety.[48] Although not statistically different from zero (*p*-value .09), the coefficients corresponding to scrams are estimated with enough precision to reject reasonably small (>5%) increases. Moreover, the point estimates are large compared to the mean, implying a 30% decrease in scrams after divestiture. This is consistent with a widely-held view in the nuclear industry that there are complementarities between safety and

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[46] This cost range comes from Tom Weir, the Senior Vice President for Engineering at Framatome ANP (now Areva), a leading international nuclear firm as quoted in Fabian, Thecla, "New Plant from Old," *Nuclear Engineering International*, September 12, 2005. At $900 per kilowatt of added capacity, typical average wholesale electricity prices ($60 per MWh), and a 90% capacity factor a reactor owner would pay for the investment in about 2 years.

[47] We also tested whether reactors operated by independent power producers are systematically more likely to be operating when wholesale electricity prices are high. Using daily data from U.S. Department of Energy, Energy Information Administration, "Wholesale Market Data from Intercontinental Exchange" for six major trading hubs from 2001-2009 we estimated alternative specifications with the divestiture indicator, the wholesale price, and the interaction between the two. Including these additional covariates has essentially no impact on the estimated coefficient for divestiture and the estimated coefficient corresponding to the interaction term is close to zero and statistically insignificant. From Figure 5 it is clear that both investor-owned utilities and independent power producers tend overwhelmingly to perform refueling and maintenance during the spring and fall when wholesale prices are low. Given that outages are already being performed during these periods and that most outages are planned long in advance, there seems to be little scope for increased efficiency along this margin.

[48] David, Maude-Griffin, and Rothwell (1996), for example, show that scrams decreased after the Three Mile Island accident and efforts by the NRC to increase reactor safety.

operating efficiency.[49] Profit maximization requires that reactors run *reliably* for thousands of hours a year, and component failures and other forms of unplanned outages are bad for both safety and profits. This is true both in the short-run and in the long-run, as reactors with poor safety records receive increased regulatory scrutiny and an increased probability of extended safety-related shutdowns. It is important to keep in mind, however, that this is only one, highly-imperfect, measure of nuclear reactor safety so these results should be interpreted with caution.

Panel (B2) pushes further on reactor outages – asking whether the decrease in outage days is being driven by *fewer* or *shorter* outages. The results in this panel are interesting and suggestive but mostly not statistically significant. Divestiture is associated with an 8% decrease in the number of outages per year, and a 30% decrease in the mean outage length, but neither are statistically significant with the full set of covariates.[50] The lack of precision makes it impossible to make definitive statements but it appears that outage length may be the more important of the two.

Finally, Panel (C) examines capacity factor conditional on operating. Consistent with the graphical analysis above, these results provide no evidence that reactors that have been divested are operated at higher intensity when they are operating. After adding reactor fixed effects the estimates are positive but small in magnitude and not statistically significant.

In summary, Table 7 describes three possible mechanisms that could lead to increased monthly generation at divested reactors. Ignoring within-day differences, a reactor will generate more electricity if it produces more when at maximum capacity (panel A), is available more days (panel B), or produces at a higher capacity factor when available (panel C). The results suggest that the increase in operating efficiency is primarily explained by the first two channels: an increase in maximum capacity and a decrease in outages.

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[49] For example, Hubert Miller of the NRC explains, "Most people have gotten the understanding if you… emphasize safety and managing things better, it has a positive effect on the bottom line," as quoted in Matthew L. Wald "Despite Fear, Deregulation Leaves Nuclear Reactors Working Harder, Longer, and Safer" *New York Times*, February 18, 2001.

[50] An alternative would have been to model outage length using a duration model. For instance, we could have used a Cox proportional hazard model to describe the probability than an outage ends. The advantage of least squares, however, is that it is more transparent and requires weaker identifying assumptions. Duration models are particularly well suited for contexts in which there is a large amount of censoring. Outages are relatively short and frequent compared to the sample length so this is not particularly important. A duration model would also allow us to examine how the probability that an outage finishes varies with the duration of the spell (e.g. positive or negative duration dependence), but again this is not particularly important in this context.

These two factors together imply a total increase in efficiency about as large as the baseline estimate in Section 6.[51]

7 Concluding Comments

This paper examines an unprecedented period of deregulation and consolidation in the U.S. nuclear power market. We analyze operating efficiency from before, during, and after market restructuring using a unique, high-quality dataset that describes reactor-level operations over a 40-year period. We find that deregulation and consolidation are associated with a 10% increase in operating efficiency, with similar increases across reactors of different types, manufacturers, and vintages. This central result is robust across a variety of alternative sets of control variables and specification checks. In additional analyses aimed at understanding the mechanisms driving these results we show that the increase in operating efficiency has occurred, most importantly, by decreasing the number of outage days per year.

These results provide some of the clearest evidence to date of efficiency gains from the deregulation of electricity markets. As predicted by economic theory, removing regulation has provided incentives for firms to increase efficiency, reduce costly outages, and make prudent investments in capacity. As plants have been sold to private companies the financial cost of poor operating efficiency has transferred from ratepayers to shareholders, and companies like Exelon and Entergy have responded by achieving the highest levels of nuclear reactor operating efficiency in history. Each additional operating hour for a typical nuclear power plant represents about $120,000 in profit – and these companies have worked hard to make sure their plants are operating as much as possible.

Our paper also highlights an important relationship between nuclear operating efficiency and the environment. We find that over this period the increase in electricity production from nuclear plants associated with divestiture implies more carbon abatement than all U.S. wind and solar generation combined. This reflects the fact that nuclear generation represents a large share of the electricity market, particularly compared to wind and solar which are growing but continue to represent a relatively small

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[51] The total increase in operating efficiency implied in Table 7 is very similar to the point estimate in column (1) of Table 3. The point estimates in columns (2-5) of Table 3 indicate a somewhat larger total increase in part because with the longer pre-period available in the monthly data once reactor fixed effects are included the coefficient estimates are larger, reflecting the fact that divested reactors tended to underperform during the 1980s and 1990s.

share. Nonetheless, one of the broader lessons from our analysis is that even modest improvements in the operating efficiency of conventional technologies can have substantial environmental implications when that technology makes up a large share of the total market.

It is important to emphasize that operating efficiency is only one part in a broader set of considerations in evaluating the overall impact of electricity deregulation. Much of the economic literature has focused on how industry restructuring affects incentives for investment behavior, and entry/exit, as well as on the potential for centralized wholesale markets to increase efficiency. These considerations likely have significant consequences for welfare, particularly in the long-run. A related and perhaps even more important issue is the effect of restructuring on the risk of nuclear accidents. Our results provide mild evidence that one measure of reactor safety may have actually improved with divestiture, but this area remains an important priority for future work.

References

Aigner, Dennis J. and Shih-Fan Chu. 1968. “On Estimating the Industry Production Function,” *American Economic Review*, 58: 826-839.

Aigner, Dennis J., C.A. Knox Lovell, and Peter Schmidt. 1977. “Formulation and Estimation of Stochastic Frontier Production Function Models,” *Journal of Econometrics*, 6: 21-37.

Alchian, Armen. 1963. “Reliability of Progress Curves in Airframe Production,” *Econometrica* 31, 679-694.

Altonji, Joseph G., Todd E. Elder and Christopher R. Taber. 2005. “Selection on Observed and Unobserved Variables: Assessing the Effectiveness of Catholic Schools,” *Journal of Political Economy*, 113(1), 151-184.

Averch, Harvey and Leland L. Johnson. 1962. "Behavior of the Firm Under Regulatory Constraint,” *American Economic Review* 52(5): 1052–1069.

Berry, Steven T. and Joel Waldfogel. 2001. “Do Mergers Increase Product Variety? Evidence from Radio Broadcasting,” *Quarterly Journal of Economics*, 116(3): 1009-1025.

Borenstein, Severin. 2008. “The Market Value and Cost of Solar Photovoltaic Electricity Projection,” *CSEM Working Paper # 176*.

Borenstein, Severin, James Bushnell, and Frank Wolak. 2002. “Measuring Market Inefficiencies in California’s Restructured Wholesale Electricity Market,” *American Economic Review*, 92(5): 1376-1405.

Bushnell, James, Erin Mansur and Celeste Saravia. 2008. “Vertical Arrangements, Market Structure, and Competition: An Analysis of Restructured U.S. Electricity Markets,” *American Economic Review*, 98(1): 237-266.

Bushnell, James B. and Catherine Wolfram. 2005. “Ownership Change, Incentives and Plant Efficiency: The Divestiture of U.S. Electric Generation Plants,” *CSEM Working Paper Number 140*.

Christensen, Lauritis R. and William H. Greene. 1976. “Economies of Scale in U.S. Electric Power Generation.” *Journal of Political Economy*. 84(4): 655-76.

Craig, J. Dean and Scott J. Savage. 2011. "Market Restructuring, Competition and the Efficiency of Electric Generation: Plant-Level Evidence from the United States 1996 to 2006", *University of Colorado Working Paper*.

Dafny, Leemore, Mark Duggan and Subramaniam Ramanarayanan. forthcoming. "Paying a Premium on your Premium? Consolidation in the U.S. Health Insurance Industry." *American Economic Review*.

David, Paul A., Roland Maude-Griffin and Geoffrey Rothwell. 1996. "Learning by Accident? Reductions in the Risk of Unplanned Outages in U.S. Nuclear Power Plants After Three Mile Island." *Journal of Risk and Uncertainty*, 13: 175-198.

Fabrizio, Kira R., Nancy L. Rose, and Catherine D. Wolfram. 2007. "Do Markets Reduce Costs? Assessing the Impact of Regulatory Restructuring on U.S. Electric Generation Efficiency." *American Economic Review*, 97(4), 1250-1277.

Focarelli, Dario and Fabio Panetta. 2003. "Are Mergers Beneficial to Consumers? Evidence from the Market for Bank Deposits." *American Economic Review*, 93(4): 1152-1172.

Hausman, Catherine. 2011. "Corporate Incentives and Nuclear Safety." UC Berkeley Working Paper, May 2011.

Hortascu, Ali and Chad Syverson. 2007. "Cementing Relationships: Vertical Integration, Foreclosure, Productivity, and Prices." *Journal of Political Economy*, 115(2): 250-301.

Hortacsu, Ali and Steve Puller. 2008. "Understanding Strategic Bidding in Multi-Unit Auctions: A Case Study of the Texas Electricity Spot Market." *RAND Journal of Economics*, 39(1): 86–114.

Hortacsu, Ali, Seyed Ali Madanizadeh and Steve Puller. 2010. "Power to Choose: An Analysis of Consumer Behavior in the Texas Retail Electricity Market." *Working paper.*

Irwin, Douglas A. and Peter J. Klenow. 1994. "Learning-by-Doing Spillovers in the Semiconductor Industry," *Journal of Political Economy* 102, 1200-1227.

Joskow, Paul L. 1982. "Problems and Prospects for Nuclear Energy in the United States." in Energy, Economics, and the Environment, ed. Gregory A. Daneke, Lexington: D.C. Heath and Company.

Joskow, Paul L. 1997. "Restructuring, Competition and Regulatory Reform in the U.S. Electricity Sector." *Journal of Economic Perspectives* 11: 119-138.

Joskow, Paul L. 2005. **"**Regulation and Deregulation After 25 Years: Lessons Learned for Research in Industrial Organization." *Review of Industrial Organization* 26 (2), 169-193.

Joskow, Paul L. 2011. "Comparing the Costs of Intermittent and Dispatchable Electricity Generating Technologies." *American Economic Review*, 101(3): 238-241.

Joskow, Paul L. and John E. Parsons. 2009. "The Economic Future of Nuclear Power." *Daedalus*, 138(4): 45-59.

Joskow, Paul L. and Nancy L. Rose. 1989. "The Effects of Economic Regulation." In Handbook of Industrial Organization, North Holland.

Joskow, Paul L. and Nancy L. Rose. 1985. "The Effects of Technological Change, Experience, and Environmental Regulation on the Construction Cost of Coal-Burning Generating Units." *RAND Journal of Economics* 16(1), 1-17.

Joskow, Paul L. and George A. Rozanski. 1979. "The Effects of Learning by Doing on Nuclear Plant Operating Reliability." *Review of Economics and Statistics*, 61(2), 161-168.

Kleit, Andrew and Dek Terrell. 2001. "Alternative Regulatory Methods and Firm Efficiency: Stochastic Frontier Evidence from the U.S. Electricity Industry." *Review of Economics and Statistics*, 83(3), 523-530.

Knittel, Christopher R. 2002. "Alternative Regulatory Methods and Firm Efficiency: Stochastic Frontier Evidence from the U.S. Electricity Industry." *Review of Economics and Statistics*, 84(3), 530-540.

Mansur, Erin and Matthew White. 2010. "Market Organization and Efficiency in Electricity Markets." *Working paper*.

Lester, Richard K. and Mark J. McCabe. 1993. "The Effect of Industrial Structure on Learning By Doing in Nuclear Power Plant Operation." *RAND Journal of Economics*, 24(3), 418-438.

Massachusetts Institute of Technology (MIT). 2003. "The Future of Nuclear Power: An Interdisciplinary MIT Study." MIT Energy Initiative.

Massachusetts Institute of Technology (MIT). 2009. "The Future of Nuclear Power: An Interdisciplinary MIT Study." MIT Energy Initiative.

Olley, G. Steven and Ariel Pakes. 1996. "The Dynamics of Productivity in the Telecommunications Equipment Industry." *Econometrica*, 64(6), 1263-1297.

Peltzman, Sam and Clifford Winston. 2000 Deregulation of Network Industries: What's Next? Washington, DC: Brookings Institution

Rothwell, Geoffrey. 1990. "Utilization and Service: Decomposing Nuclear Reactor Capacity Factors." *Resources and Energy*, 12, 215-229.

Rothwell, Geoffrey. 1996. "Organizational Structure and Expected Output at Nuclear Power Plants." *Review of Economics and Statistics*, Vol. 78 (3), 1996, pp. 482-488.

Shanefelter, Jennifer K. 2008. "Restructuring, Ownership and Efficiency: The Case of Labor in Electricity Generation." *Department of Justice Working Paper, EAG 200812.*

Thornton, Rebecca A. and Peter Thompson. 2001. "Learning from Experience and Learning from Others: An Exploration of Learning and Spillovers in Wartime Shipbuilding," *American Economic Review*, 91, 1350-1368.

Verma, Kiran, Barry M. Mitnick, and Alfred A. Marcus. 1999. "Making Incentive Systems Work: Incentive Regulation in the Nuclear Power Industry." *Journal of Public Administration Research and Theory*, 9 (3), 395-436.

White, Matthew. 1996. "Power Struggles: Explaining Deregulatory Reforms in Electricity Markets." *Brookings Papers on Microeconomics*, 201-267.

Winston, Clifford. 1993. "Economic Deregulation: Days of Reckoning for Microeconomists." *Journal of Economic Literature*, 31(3): 1263-1289.

Wolfram, Catherine. 1999. "Measuring Duopoly Power in the British Electricity Spot Market." *American Economic Review*, 89(4): 805-826.

Wolfram, Catherine. 2004. "The Efficiency of Electricity Generation in the U.S. After Restructuring." in James Griffin and Steve Puller, eds., Electricity Deregulation: Choices and Challenges. University of Chicago Press: Chicago, IL.

Zhang, Fan. 2007. "Does Electricity Restructuring Work? Evidence From The U.S. Nuclear Energy Industry." *Journal of Industrial Economics*, 55(3): 397-418.

Figure 1: Net Generation Scaled By Reactor Design Capacity, 1970-2009

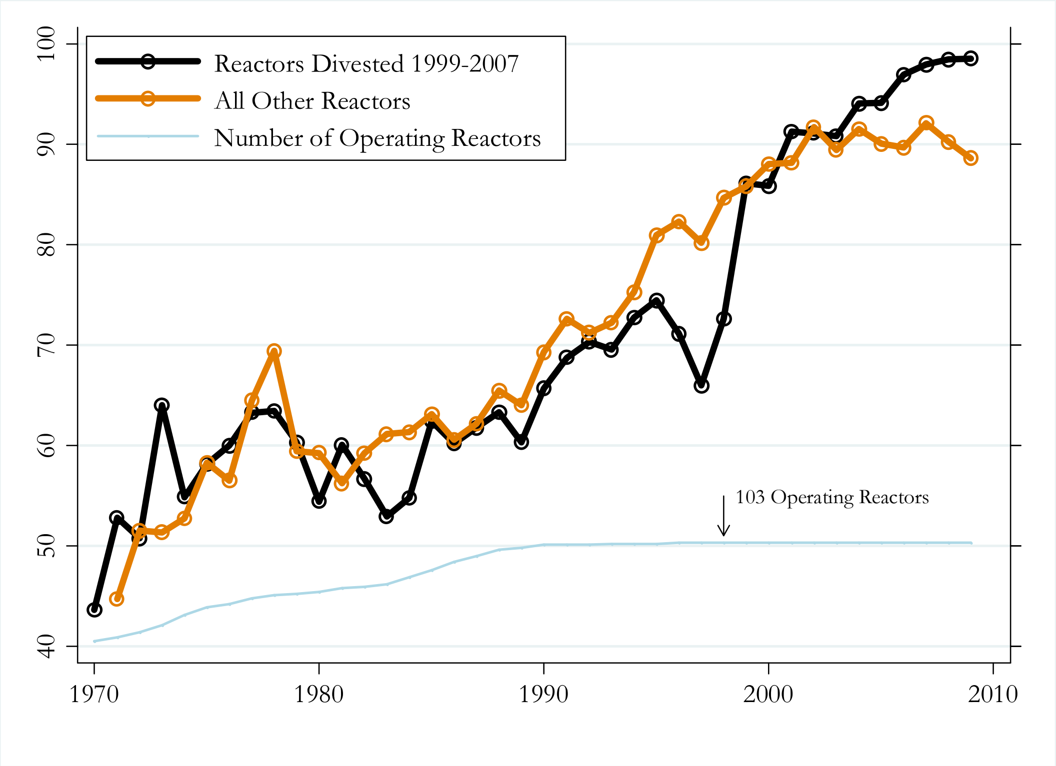

Figure 2: The Effect of Divestiture on Operating Efficiency by Month of Year

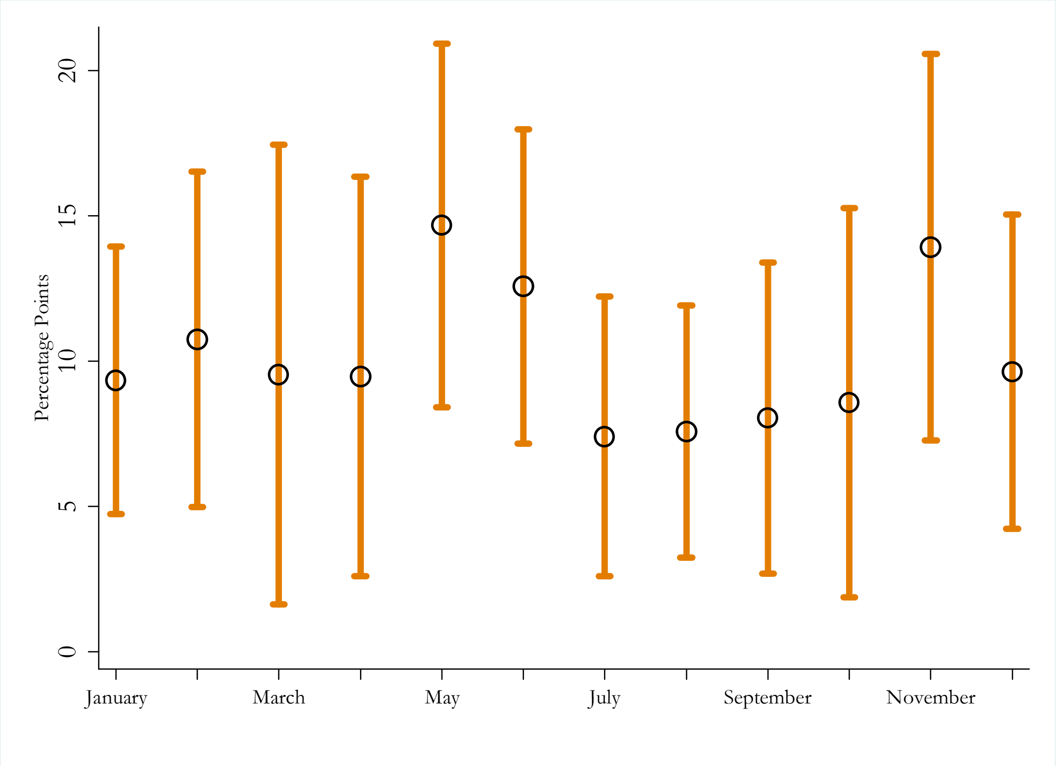

Figure 3: Number of Reactors Operated by the Same Operator, 1970-2009

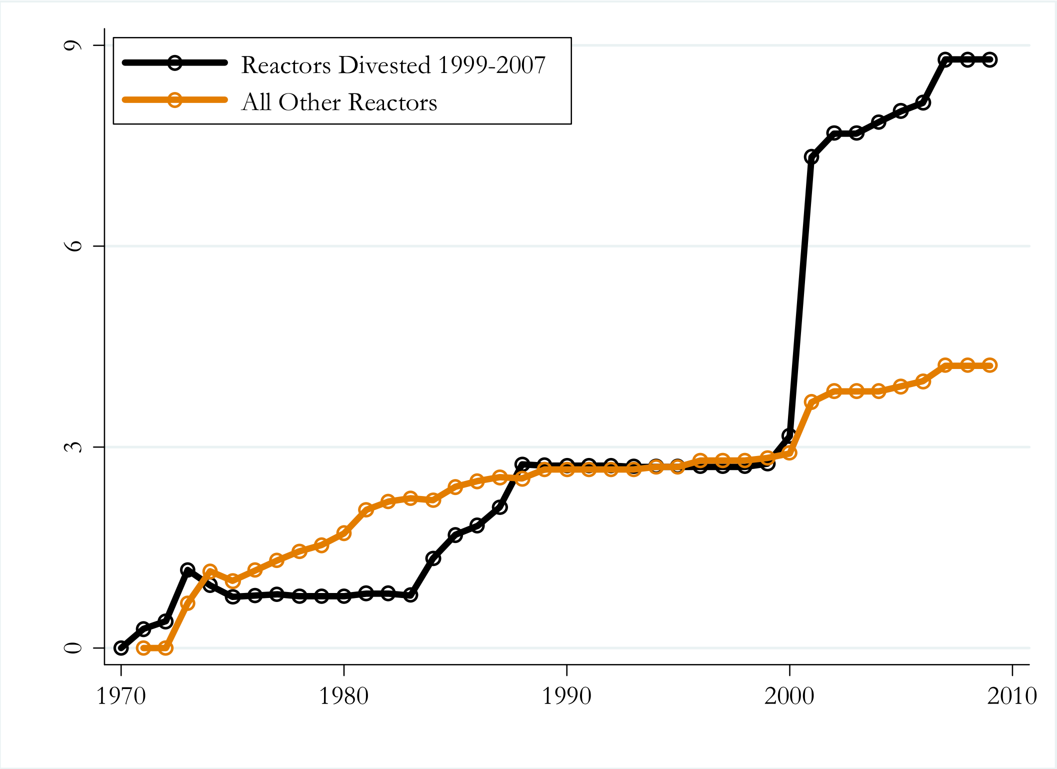

Figure 4: Maximum Licensed Thermal Capacity as a Percent of Design Capacity, 1970-2009

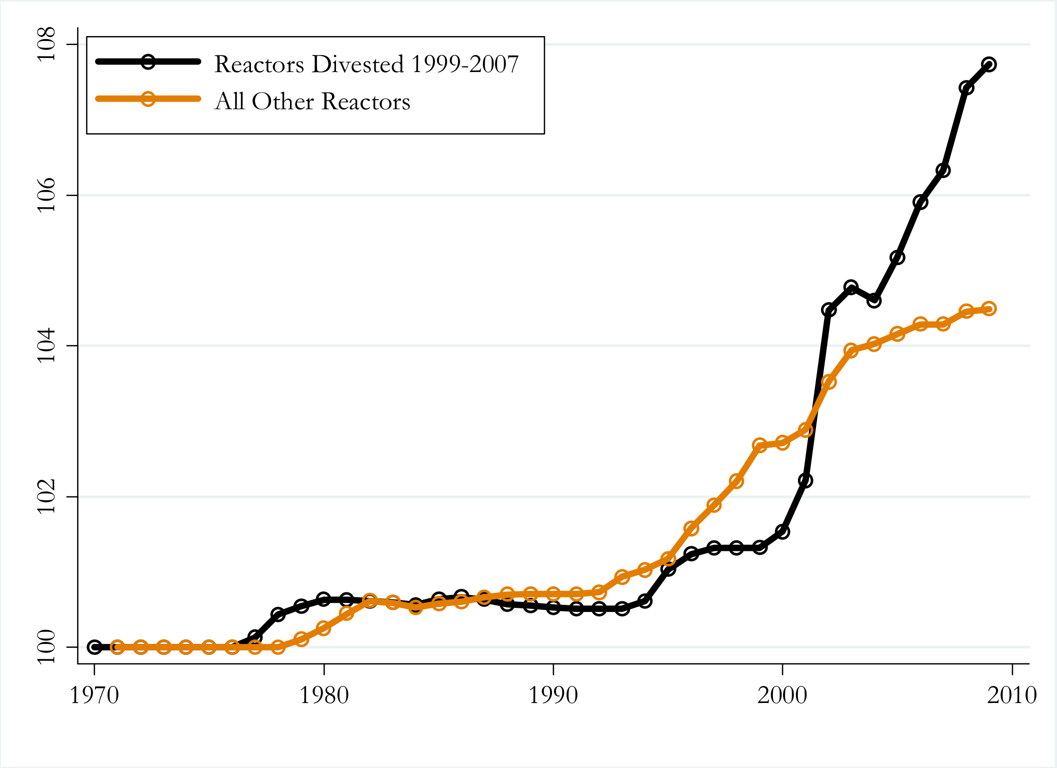

Figure 5: Fraction of Reactors Not Operating By Day, 1999-2009

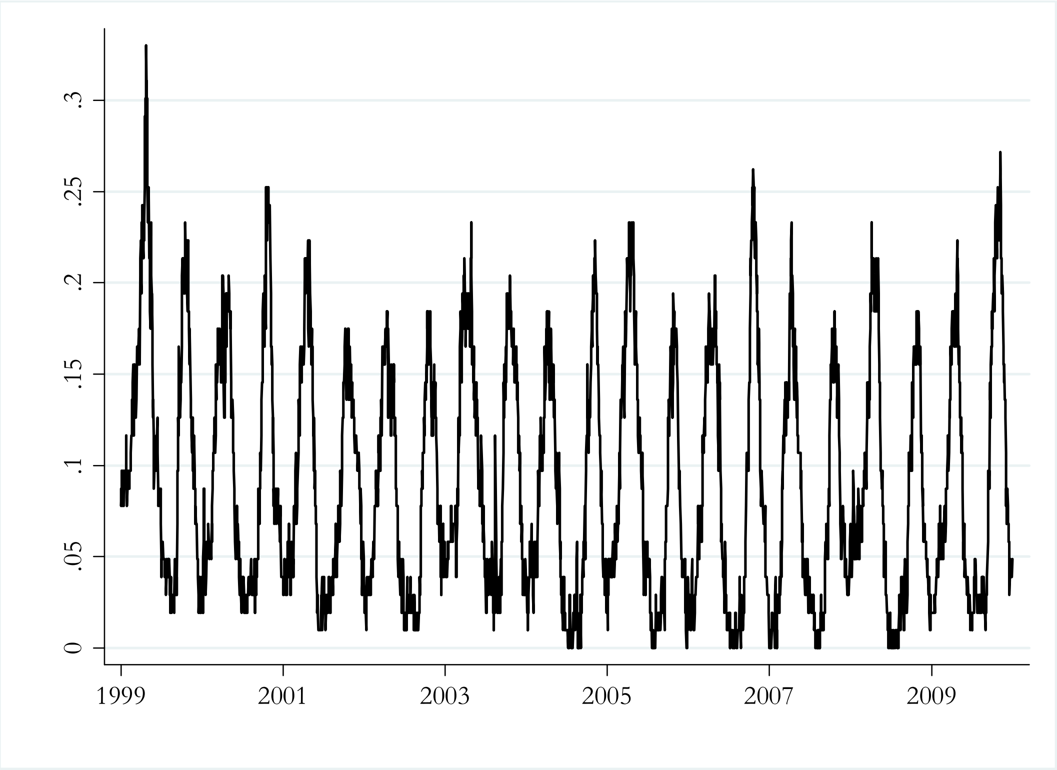

Figure 6: Fraction of Reactors Not Operating By Day of Year, 2005-2009

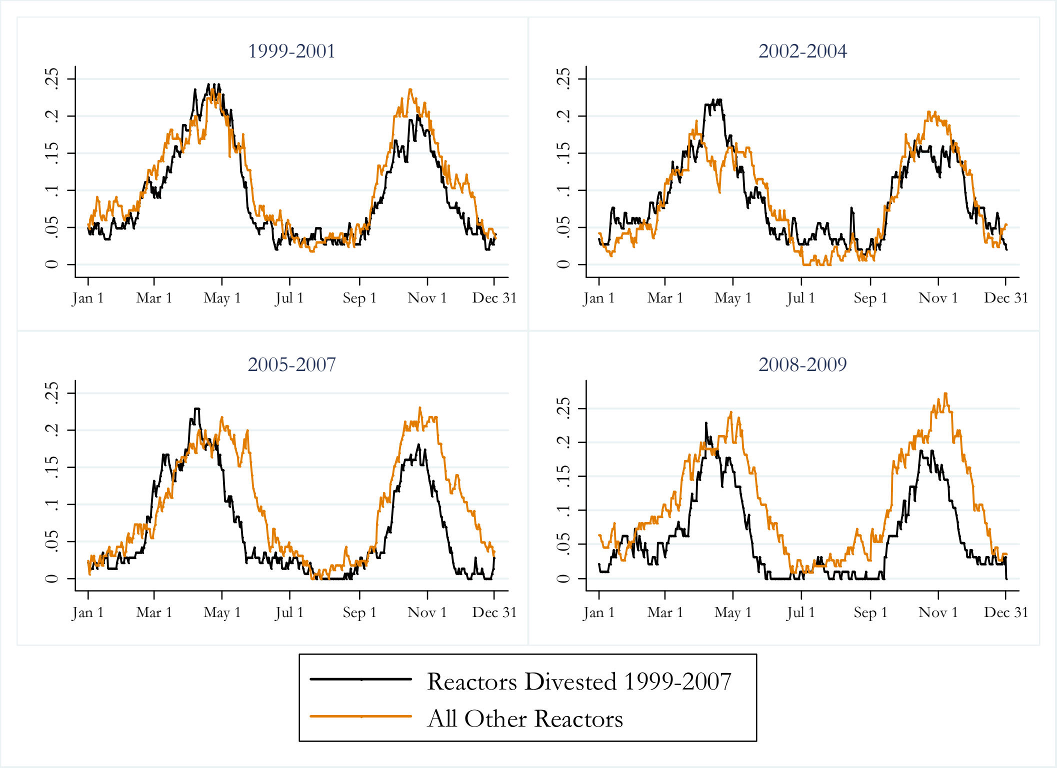

Figure 7: Mean Number of Outage Days Per Reactor, 1999-2009

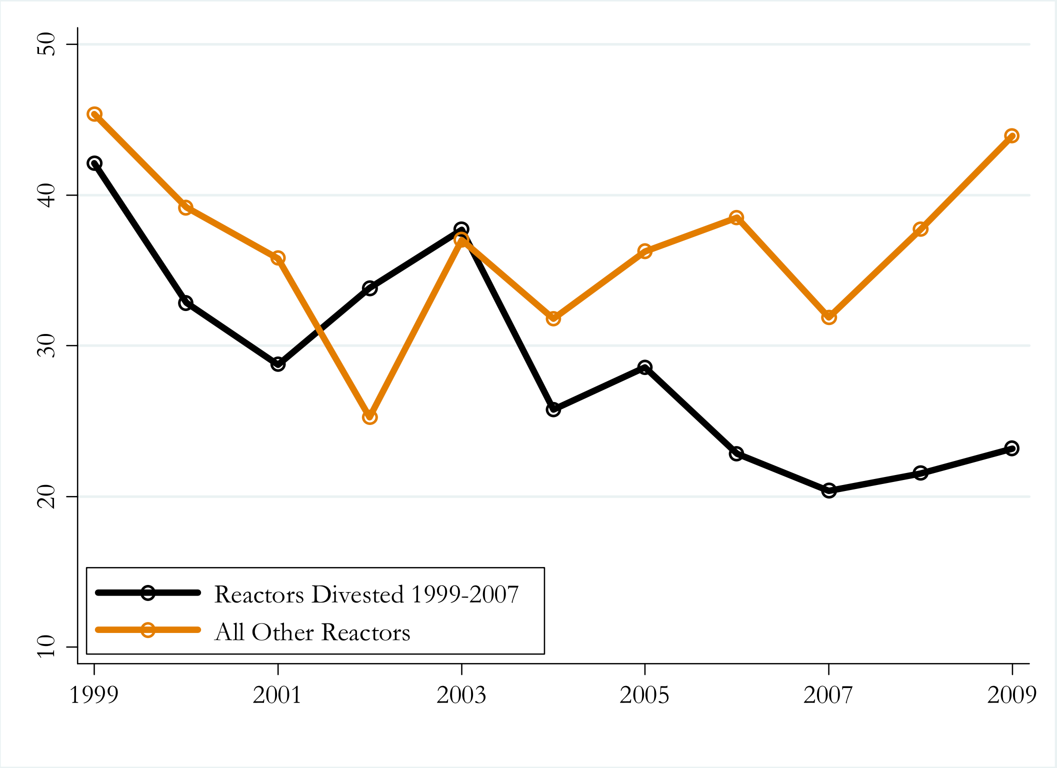

Figure 8: Mean Number of Scrams per Hour of Reactor Operation, 1999-2009

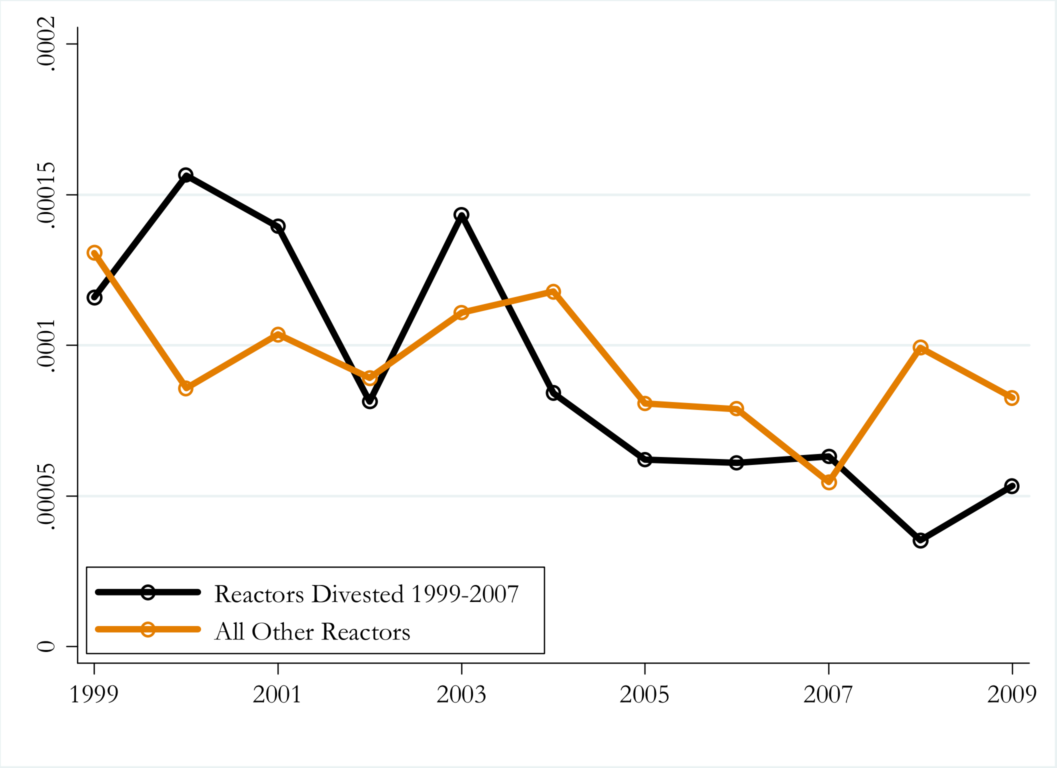

Figure 9: Mean Capacity Factor by Day of Year for Operating Reactors, 2005-2009

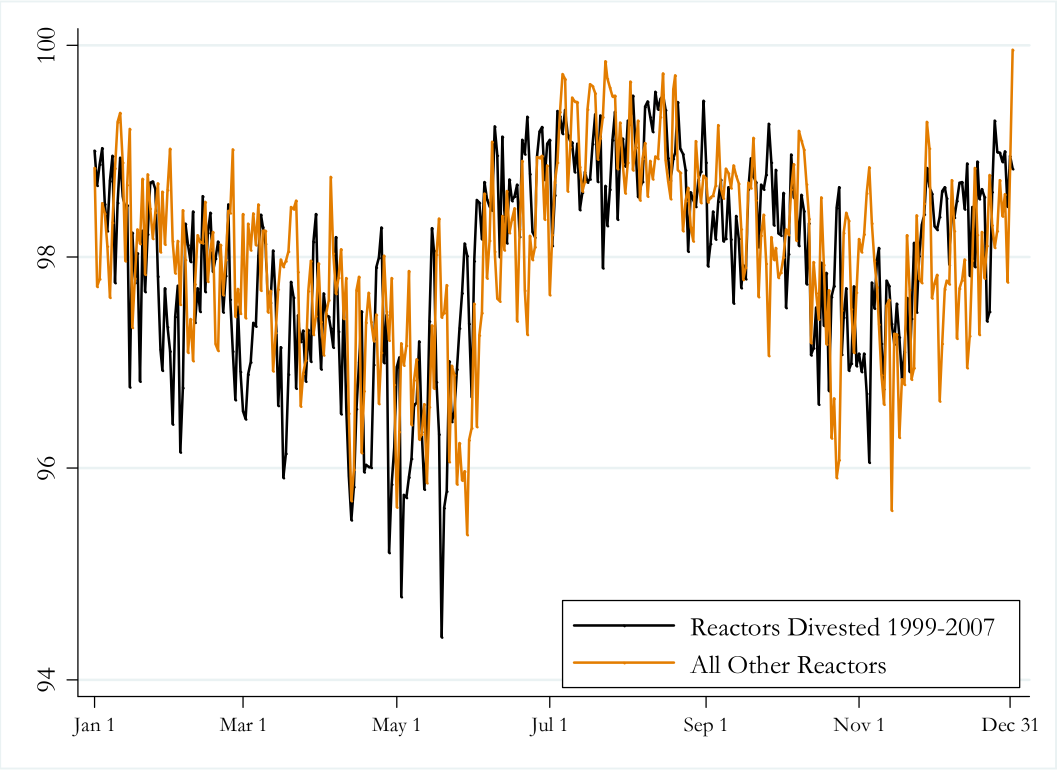

TABLE 1

Descriptive Statistics: U.S. Nuclear Power Reactors

A. Reactor Characteristics (103 total reactors)

Number of Reactors By Vintage	
1960s	2
1970s	50
1980s	46
1990s	5
Number of Reactors By Type	
Pressurized Water Reactor	69
Boiling Water Reactor	34
Number of Reactors By Manufacturer	
Westinghouse	48
General Electric	34
Combustion Engineering	14
Babcock and Wilcox	7

Notes: Our sample includes all reactors that were operating as of January 1, 2000. Vintage, reactor type, and reactor manufacturer come from the *NRC Information Digest 2010-2011* (NUREG-1350, Volume 22), published August 2010. Vintage is defined as the decade the reactor began commercial operation.

TABLE 1 (continued)

Descriptive Statistics: U.S. Nuclear Power Reactors

B. Operating Efficiency and Reactor Outages

Net Generation as a Percent of Design Capacity (Department of Energy)	
1970s	61%
1980s	61%
1990s	75%
2000s	92%
Daily Reactor Status 1999-2009 (Nuclear Regulatory Commission)	
Proportion of Daily Observations at 100% Capacity Factor	0.77
Proportion of Daily Observations at 90% - 99%	0.09
Proportion of Daily Observations at 1% - 89%	0.04
Proportion of Daily Observations at 0%	0.09
Outages 1999-2009 (Nuclear Regulatory Commission)	
Proportion Manual Shutdown for Refueling	0.73
Proportion Manual Shutdown for Other Reasons	0.24
Proportion Automatic Shutdown (“scram”)	0.02

Notes: This table describes operating efficiency and reactor outages for the 103 U.S. nuclear power reactors that were operating in the United States as of January 1, 2000. Capacity factor in the first four rows was calculated by the authors by dividing generation levels from U.S. Department of Energy, Energy Information Administration, *Power Plant Report* (EIA-906), 1970-2009 by design capacity (in MWe) from U.S. Department of Energy, Energy Information Administration, *Nuclear Power Generation and Fuel Cycle Report 1997*, “Appendix C: Nuclear Units Ordered in the United States, 1953-1996”. Daily reactor status and explanations for outages come from U.S. NRC, *Power Status Reports*.

TABLE 2

Comparing Divested With Non-Divested Nuclear Reactors

	(1) Reactors Divested 1999-2007 (n=48)	(2) All Other Reactors (n=55)	(3) *p*-value (1) vs (2)
Reactor Characteristics			
Mean Design Capacity (in MWe)	921.9	959.7	.38
Mean Reactor Age as of December 1998	18.8	18.4	.74
Number of Reactors Operated by the Same Reactor Operator as of December 1998	2.7	2.8	.86
Original Construction Cost Per Kilowatt Capacity (in Year 2010 dollars)	$2,397	$2,298	.81
Reactor Type			
Proportion Pressurized Water Reactor	0.54	0.78	.01
Proportion Boiling Water Reactor	0.46	0.22	.01
Reactor Manufacturer			
Proportion Westinghouse	0.42	0.51	.35
Proportion General Electric	0.46	0.22	.01
Proportion Combustion Engineering	0.08	0.18	.15
Proportion Babcock and Wilcox	0.04	0.09	.33
Reactor Location			
Proportion Northeast Census Region	0.50	0.00	.00
Proportion Midwest Census Region	0.38	0.18	.03
Proportion South Census Region	0.13	0.67	.00
Proportion West Census Region	0.00	0.15	.01

Notes: The sample includes all 103 nuclear power reactors operating in the United States as of January 1, 2000. Year the reactor began commercial operation, reactor type, reactor manufacturer, and reactor location come from the *NRC Information Digest 2010-2011* (NUREG-1350, Volume 22), published August 2010. Original construction cost per kilowatt was calculated by the authors using data from FERC, Form 1 for 1996. Column (3) reports *p*-values from tests that the means are equal in the two subsamples.

TABLE 3

The Effect of Divestiture on Nuclear Operating Efficiency

	(1)	(2)	(3)	(4)	(5)
$1[Divested]_{\text{it}}$	6.5**	10.4**	10.2**	10.2**	9.7**
	(1.2)	(2.1)	(2.0)	(2.0)	(2.0)
Month Fixed Effects (480 total months)	Yes	Yes	Yes	Yes	Yes
Reactor Fixed Effects (103 total reactors)	No	Yes	Yes	Yes	Yes
Reactor Age (cubic)	No	No	Yes	Yes	Yes
Observations Weighted By Reactor Capacity	No	No	No	Yes	No
Dataset Collapsed To Plant Level	No	No	No	No	Yes
Number of Cross Sectional Units	103	103	103	103	65
Number of Observations	36,667	36,667	36,667	36,667	22,632
R^2	.18	.22	.22	.22	.26

Notes: This table reports coefficient estimates and standard errors corresponding to an indicator variable for reactors that have been divested from five separate regressions. In all regressions the dependent variable is net generation as a percent of design capacity. The sample includes monthly observations 1970-2009 for all 103 nuclear power reactors operating in the United States as of January 1, 2000. Standard errors are clustered at the plant level. Single and double asterisks denote statistical significance at the 5% and 1% level.

TABLE 4

The Effect of Divestiture By Reactor Type, Manufacturer, and Vintage

	(1) By Reactor Type	(2) By Reactor Manufacturer	(3) By Vintage
Pressurized Water Reactors (n=69)	9.5** (2.5)		
Boiling Water Reactors (n=34)	10.8** (2.7)		
Westinghouse (n=48)		10.0** (2.9)	
General Electric (n=34)		10.8** (2.7)	
Combustion Engineering (n=14)		5.9 (3.4)	
Babcock and Wilcox (n=7)		12.5** (1.9)	
Completed Before 1975 (n=31)			10.3** (2.7)
Completed 1975 - 1985 (n=38)			13.7** (3.6)
Completed After 1985 (n=34)			7.2** (2.6)
Month Fixed Effects (480 total months)	Yes	Yes	Yes
Reactor Fixed Effects (103 total reactors)	Yes	Yes	Yes
Reactor Age (cubic)	Yes	Yes	Yes
Number of Observations	36,667	36,667	36,667
R^2	.22	.22	.22

Notes: This table reports coefficient estimates and standard errors from three separate regressions. In all regressions the dependent variable is net generation as a percent of design capacity. Coefficients are reported from interaction terms between the variables indicated in the row headings and an indicator variable for reactors that have been divested The sample includes monthly observations 1970-2009 for all 103 nuclear power reactors operating in the United States as of January 1, 2000. Standard errors are clustered at the plant level. Single and double asterisks denote statistical significance at the 5% and 1% level. In none of the three regressions is it possible to reject the null hypothesis that the estimated coefficients are equal. The *p*-values from the three tests of equal coefficients are .68, .12, and .31, respectively.

TABLE 5

The Effect of Divestiture and Consolidation on Nuclear Operating Efficiency

	(1) Reactor-Level	(2) Reactor-Level	(3) Reactor-Level	(4) Reactor-Level	(5) Reactor-Level	(6) Plant-Level
$1[Divested]_{it}$	10.2** (2.0)	7.8** (2.3)	8.4** (1.9)	8.7** (2.1)	*Excluding Divested Reactors*	6.7** (2.1)
Number of Reactors/Plants Operated by the Same Operator	--	.48 (.28)	--	--	.87* (.34)	.95* (.39)
Number of Same-Type Reactors (PWR/BWR) Operated by the Same Operator	--	--	.64 (.44)	--	--	--
Number of Same-Manufacturer Reactors Operated by the Same Operator	--	--	--	.61 (.43)	--	--
Month Fixed Effects (480 total months)	Yes	Yes	Yes	Yes	Yes	Yes
Reactor/Plant Fixed Effects (103 total reactors)	Yes	Yes	Yes	Yes	Yes	Yes
Reactor/Plant Age (cubic)	Yes	Yes	Yes	Yes	Yes	Yes
Mean of Consolidation Variable	-	3.3	2.1	1.7	2.9	1.5
Number of Observations	36,667	36,667	36,667	36,667	19,446	23,796
R^2	.22	.22	.22	.22	.21	.27

Notes: This table reports coefficient estimates and standard errors corresponding to an indicator variable for reactors that have been divested from four separate regressions. In all regressions the dependent variable is net generation as a percent of design capacity. In columns (1)-(4) and column (6) the sample includes monthly observations 1970-2009 for all nuclear power reactors operating in the United States as of January 1, 2000. Column (6) excludes all reactors that were ever divested, leaving 55 of the 103 total reactors. Standard errors are clustered at the plant level. Single and double asterisks denote statistical significance at the 5% and 1% level.

TABLE 6

Considering Possible Concerns About Selection Bias and Long Outages 1996-1998

	Selection Bias				Long Outages 1996-1998			
	(1) Excluding Michigan	(2) Excluding California	(3) Excluding Iowa and Wisconsin	(4) Excluding the Northeast Census Region	(5) Excluding Years 1996-1998	(6) Excluding 12+ Month Outages 1996-1998	(7) Excluding Reactors With 12+ Month Outages 1996-1998	(8) Including Indicator Variables for All 12+ Month Outages, During and After
$1[Divested]_{\text{it}}$	9.7**	10.4**	10.3**	11.0**	8.8**	9.1**	8.2**	7.4**
	(2.0)	(2.1)	(2.1)	(2.7)	(2.0)	(2.1)	(1.9)	(1.5)
Month Fixed Effects (480 total months)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reactor Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reactor Age (cubic)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of Reactors	99	99	99	77	103	103	93	103
Number of Observations	35,459	35,155	34,905	27,016	32,963	36,452	33,177	36,667
R^2	.23	.22	.23	.22	.24	.22	.23	.34

Notes: This table reports coefficient estimates and standard errors corresponding to an indicator variable for reactors that have been divested from eight separate regressions. In all regressions the dependent variable is net generation as a percent of design capacity. The sample includes monthly observations 1970-2009 for all nuclear power reactors operating in the United States as of January 1, 2000 excluding reactors or reactor-month observations as indicated in the column headings. Column (8) includes an indicator variable for any outage that lasted for 12 or more months, plus separate indicator variables for the three 12-month periods after the long outage. Standard errors are clustered at the plant level. Single and double asterisks denote statistical significance at the 5% and 1% level.

TABLE 7

Understanding Why Efficiency Increased

	(1)	(2)	(3)
	A. Maximum Generating Capacity		
Maximum Generation Over Last 12 Operating Months	2.5**	1.6	1.7
[Sample Mean: 100.4]	(0.9)	(1.5)	(1.4)
Maximum Licensed Thermal Capacity (MW_t)	1.8	1.9	1.9
[Sample Mean: 102.0]	(1.1)	(1.1)	(1.1)
	B1. Operating Days and Shutdowns		
$1[Operating]_{it}$ x 100	3.9**	3.5	3.8*
[Sample Mean: 91.0]	(0.7)	(2.0)	(1.9)
$1[Scram]_{it}$ x 100	-.02	-.06	-.06
[Sample Mean: 0.2]	(.02)	(.04)	(.04)
	B2. Length Versus Number of Outages		
Number of Outages per Year	-.17	-.13	-.13
[Sample Mean: 1.7]	(.11)	(.16)	(.16)
Mean Outage Length in Days	-6.0**	-5.7	-6.1
[Sample Mean: 20.8]	(1.2)	(4.2)	(4.0)
	C. Capacity Factor when Operating		
Capacity Factor in Percent Excluding Zeros	-0.3	0.5	0.4
[Sample Mean: 97.7]	(0.3)	(0.3)	(0.3)
Time Effects (4,017 total days / 11 total years)	Yes	Yes	Yes
Reactor Fixed Effects (103 total reactors)	No	Yes	Yes
Reactor/Plant Age (cubic)	No	No	Yes

Notes: This table reports coefficient estimates and standard errors corresponding to an indicator variable for reactors that have been divested from 24 separate regressions. The row headings list the dependent variable used in each regression. The sample in all regressions includes the 103 nuclear power reactors operating in the United States as of January 1, 2000. The regressions described in the first two rows are estimated using monthly data. All other regressions are estimated using the daily data from the NRC. Both measures of maximum generating capacity are expressed as a percent of the original design capacity. Standard errors are clustered at the plant level. Single and double asterisks denote statistical significance at the 5% and 1% level.

APPENDIX TABLE 1

U.S. Nuclear Reactors Divestitures (1999-2007)

Reactor Name	**Design Capacity**	**State**	**Sales Date**	**Seller**	**Buyer**
Pilgrim	655	MA	7/1999	Boston Edison Co	Entergy
Clinton	950	IL	12/1999	Illinois Power Co	Amergen (Exelon)
Three Mile Island 1	819	PA	12/1999	GPU Nuclear Corp	Amergen (Exelon)
Calvert Cliffs 1	845	MD	7/2000	Baltimore Gas & Electric	Constellation
Calvert Cliffs 2	845	MD	7/2000	Baltimore Gas & Electric	Constellation
Susquehanna 1	1065	PA	7/2000	Penn Power and Light	PPL Corp
Susquehanna 2	1052	PA	7/2000	Penn Power and Light	PPL Corp
Hope Creek 1	1067	NJ	8/2000	Public Service E&G	PSEG Power
Oyster Creek	650	NJ	8/2000	GPU Nuclear Corp	Amergen (Exelon)
Salem 1	1090	NJ	8/2000	Public Service E&G	PSEG Power
Salem 2	1115	NJ	8/2000	Public Service E&G	PSEG Power
Fitzpatrick	821	NY	11/2000	Power Authority of New York	Entergy
Indian Point 3	965	NY	11/2000	Power Authority of New York	Entergy
Braidwood 1	1120	IL	1/2001	Commonwealth Edison	Exelon
Braidwood 2	1120	IL	1/2001	Commonwealth Edison	Exelon
Byron 1	1120	IL	1/2001	Commonwealth Edison	Exelon
Byron 2	1120	IL	1/2001	Commonwealth Edison	Exelon
Dresden 2	794	IL	1/2001	Commonwealth Edison	Exelon
Dresden 3	794	IL	1/2001	Commonwealth Edison	Exelon
La Salle 1	1078	IL	1/2001	Commonwealth Edison	Exelon
La Salle 2	1078	IL	1/2001	Commonwealth Edison	Exelon
Limerick 1	1065	PA	1/2001	Philadelphia Electric Co	Exelon
Limerick 2	1065	PA	1/2001	Philadelphia Electric Co	Exelon
Peach Bottom 2	1065	PA	1/2001	Philadelphia Electric Co	Exelon
Peach Bottom 3	1065	PA	1/2001	Philadelphia Electric Co	Exelon
Quad Cities 1	789	IL	1/2001	Commonwealth Edison	Exelon
Quad Cities 2	789	IL	1/2001	Commonwealth Edison	Exelon
Millstone 2	870	CT	3/2001	Northeast Nuclear	Dominion
Millstone 3	1156	CT	3/2001	Northeast Nuclear	Dominion
Indian Point 2	873	NY	9/2001	Consolidated Edison Co of NY	Entergy
Nine Mile Point 1	620	NY	11/2001	Niagara Mohawk Power	Constellation
Nine Mile Point 2	1080	NY	11/2001	Niagara Mohawk Power	Constellation

APPENDIX TABLE 1 (continued)

U.S. Nuclear Reactors Divestitures 1999-2007

Reactor Name	Design Capacity	State	Sales Date	Seller	Buyer
Comanche Peak 1	1150	TX	1/2002	Texas Utilities Electric Co	TXU Generation
Comanche Peak 2	1150	TX	1/2002	Texas Utilities Electric Co	TXU Generation
Vermont Yankee	514	VT	7/2002	Vermont Yankee Nuclear Power Corporation	Entergy
Seabrook 1	1198	NH	11/2002	North Atlantic Energy Services Corporation	FPL Group
South Texas 1	1250	TX	1/2003	Reliant	CenterPoint
South Texas 2	1250	TX	1/2003	Reliant	CenterPoint
Ginna	470	NY	6/2004	Rochester Gas & Electric	Constellation
Kewaunee	535	WI	7/2005	Wisconsin Public Service	Dominion
Beaver Valley 1	835	PA	12/2005	Pennsylvania Power Company	FirstEnergy
Beaver Valley 2	852	PA	12/2005	Pennsylvania Power Company	FirstEnergy
Davis-Besse	906	OH	12/2005	Toledo Edison Co	FirstEnergy
Perry 1	1205	OH	12/2005	Cleveland Electric	FirstEnergy
Duane Arnold	538	IA	1/2006	Interstate Power And Light	FPL Group
Palisades	805	MI	4/2007	Consumers Energy Co	Entergy
Point Beach 1	497	WI	10/2007	Wisconsin Electric Power	FPL Group
Point Beach 2	497	WI	10/2007	Wisconsin Electric Power	FPL Group

Notes: Divestiture dates come from U.S. Department of Energy, Energy Information Administration, *Power Plant Report*. We identify divestitures using the first month in which a reactor operator changes its status from utility to non-utility. These dates were cross-checked against U.S. Department of Energy, Energy Information Administration, *Electric Power Monthly*, ``Electric Utility Plants That Have Been Sold and Reclassified", March Issues 2000-2003 and against SEC filings from the companies involved.