

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

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Abstract

Beginning in the late 1990s electricity markets in many U.S. states were deregulated and almost half of the nation's 103 nuclear power reactors were sold to independent power producers. Deregulation has been accompanied by substantial market consolidation and today the three largest companies control one-third of 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 duration of reactor outages. At average wholesale prices this increased efficiency is worth \$2.5 billion annually and implies an annual decrease of 35 million metric tons of carbon dioxide emissions.

Key Words: Market Deregulation, Economies of Scale, Operating Efficiency
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 basic 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 potential impact of consolidation on a number of market outcomes, including pricing, costs, investment and entry. Though firms confronting a potential merger review often argue that there will be cost efficiencies from consolidation, there is comparatively little 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 one-third of U.S. nuclear capacity.

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

² Several empirical papers examine the effect of market structure on efficiency. See, for example, Olley and Pakes (1996), Borenstein, Bushnell and Wolak (2002), Focarelli and Panetta (2003) and Syverson (2004). Most of these papers focus on efficiencies gained from reallocations across firms.

The U.S. nuclear power industry is a particularly good candidate for an empirical study of the relationship between deregulation, consolidation, and efficiency. First, electricity is a homogeneous good that is accurately and consistently measured across space and time. Second, nuclear reactors produce electricity at very low marginal cost so they are used as “baseload” generation implying that our measure of operating efficiency is unlikely to be confounded by unmodeled changes in demand.³ Third, during the relevant period there is very little entry or exit of nuclear reactors, mitigating concerns about selection that substantially complicate similar analyses. Fourth, deregulation and consolidation occurred rapidly and for only half of all reactors, lending credibility to the empirical analysis by 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, more importantly, duration of reactor outages. Efficiency gains were experienced broadly across reactors of different types, manufacturers, and vintages, with the largest increases 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 little of the deregulation-driven increase.

Our results imply a substantial increase in electricity production. In 2009 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 have important implications for the

³ Adequately controlling for demand-side factors, including quality and local demand shocks, is a key challenge in the broader productivity literature. See Syverson (2011) for a recent survey.

environment, implying an annual decrease of more than 35 million metric tons of carbon dioxide emissions. 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, deregulation is not usually envisioned as a means for achieving environmental goals.

Finally, we perform a similar analysis for one 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 emergency shutdowns, also known as “scrams.” The point estimate is relatively noisy (p -value .09), but is estimated with enough precision to reject increases larger than 5%. Safety is inherently more difficult to measure than operating efficiency. So, although we view these results as suggestive, scrams are but one, imperfect measure of safety. As more and richer data become available, it will be important to revisit this important issue.

The format of the paper is as follows. Section 2 provides background information about nuclear power and the broader electricity industry. Section 3 describes the data and empirical strategy. Section 4 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 5 presents additional results aimed at better understanding the mechanisms driving the increase in efficiency, including ancillary evidence on investments in reactor capacity and on the frequency and duration of outages. Section 6 offers concluding comments.

2 Background

2.1 Nuclear Power in the U.S. Electricity Industry

In the United States electricity is generated using coal (45%), natural gas (23%), nuclear (20%), hydro (7%), and wind, solar, and other renewables (4%).⁴ Nuclear reactors are expensive to build, but then produce power at lower marginal cost than most other generating technologies. Coal and natural gas plants produce power at higher marginal cost, but require smaller initial capital investments.⁵ 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, maintenance or in an emergency. At the other end of the spectrum are natural gas peaking plants which can be turned on and off almost instantly and with very low startup cost.

These features imply that nuclear reactors are typically used to provide baseload power, 24 hours a day. This explains why in the United States nuclear power accounts for only 10% of capacity but produces 20% of total electricity.⁶ As electricity demand peaks during the day, other forms of generation come online to meet this demand. In the United States, the fraction of electricity generated by nuclear reactors is small enough that there is enough demand to keep nuclear reactors operating even during the lowest consumption periods in the middle of the night.

Because nuclear power is baseload, the operating behavior of plants is largely unaffected by changes in electricity demand. Average fuel costs for nuclear plants (\$7 per MWh)⁷ are low compared to wholesale prices, so nuclear operators strive to minimize

⁴ 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.”

⁵ 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 8,870, 6,800, and 10,400 BTU per kilowatt hour, respectively.

⁶ 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.

⁷ 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*

planned and unplanned outages. From an empirical perspective this is advantageous because it essentially eliminates concerns about changes in observed operating efficiency being correlated with observed or unobserved changes in demand.⁸ Similarly, the entry or exit of other generating units does not typically have any effect on how nuclear plants are operated because in all cases the reactors continue to provide baseload generation.

Nuclear plants are very large so even small improvements in operating efficiency imply substantial amounts of electricity. Consider, for example, a typical two-reactor 2000 megawatt nuclear plant. 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. Given the low marginal cost of nuclear generation, this is essentially all profit.

2.2 The Regulation and Deregulation of the U.S. Electricity Industry

Traditionally electricity was regarded as a natural monopoly. In the standard regulatory model, used in various forms in many states today, utilities receive exclusive rights to provide electricity within given geographic areas and charge rates set by cost-of-service regulation. A vertically-integrated utility typically performs 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.

Under cost-of-service regulation, rates are set to allow utilities to recover their recurring operating expenses. This creates little incentive for companies to operate their plants efficiently because they receive this compensation regardless of the level of

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.

⁸ Syverson (2011) makes the point that, “[b]ecause producer-specific prices are unobserved in most business-level microdata, output is typically measured by revenue divided by an industry-level deflator. This means that within-industry price differences are embodied in output and productivity measures. If prices reflect in part idiosyncratic demand shifts or market power variation across producers—a distinct likelihood in many industries—then high “productivity” businesses may not be particularly technologically efficient. Much of the literature described above therefore documents the joint influence of productivity *and* demand factors that show up in within-industry price variation.”

performance. Poor operating efficiency at a utility's nuclear plant, for example, means that it must operate other higher-cost generating units more. Rates are then adjusted, however, to reflect these increased costs. While in theory a regulator could disallow costs for a utility with poor nuclear operating efficiency, this rarely happens in practice.

Recognizing that traditional cost-of-service regulation provides little incentive for cost-minimization, several states implemented some form of incentive regulation in the 1980s and early 1990s. These policies varied from state to state but in all cases were designed to create incentives for firms to increase output and cut costs. Some states implemented incentive programs tied to the operation of particular plants, including nuclear plants. Empirical work at the time found that the incentive programs had mixed success at raising average capacity factors at nuclear plants (Verma, Mitnick and Marcus, 1999).

In part as a response to the limitations of cost-of-service 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. Many regulators were concerned that vertically integrated companies could distort the wholesale markets, as they would serve as both buyers and sellers into these markets, as well as owners of the transmission grid to which any nonutility supplier would need access. 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 time 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.⁹ The timing of the nuclear plant divestitures followed the broader industry trend.

A number of empirical papers have evaluated the effects of U.S. electricity restructuring, including its impact on the efficiency of wholesale power markets (Borenstein, Bushnell and Wolak, 2002; Bushnell, Mansur and Saravia, 2008; and Hortacsu 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 1992-1998, prior to the beginning of plant divestitures. Our analysis adds 10+ years of additional data from the key period *after* deregulation, as well as 20+ years of data from before 1992.

Both academics and regulators have devoted considerable attention to identifying and mitigating market power in deregulated wholesale markets (see, e.g., Wolfram 1999, Borenstein, Bushnell, and Wolak 2002, and Joskow and Kahn, 2002). To prevent the exercise of market power, regulators have established bid caps, set up market monitoring commissions, and blocked attempted mergers. Whatever market power was present during the time period we study, it is unlikely to have influenced nuclear plant operations. Operators of nuclear reactors typically will not attempt to exercise market power unilaterally. Because the marginal cost of nuclear power is low relative to typical market clearing prices, the operator of a nuclear plant would need to submit a bid substantially above its marginal cost in order to influence prices. And bidding above marginal cost is risky because if demand ends up being different than expected, or if other generators bid differently than expected, the nuclear plant can find itself out of the queue and not producing power. This is particularly costly for a nuclear plant because it means that it

⁹ Table 1.1 in U.S. Department of Energy, Energy Information Administration, *Electric Power Annual*, DOE/EIA-0226, revised April 2011.

does not receive the substantial inframarginal rent that it would otherwise receive. Moreover, because of the long ramping times for nuclear reactors, it may be several days before the plant can operate again at full power.

The real scope for market power comes, instead, from companies that operate a portfolio of nuclear and non-nuclear generating plants. A diversified company may find it profitable to withhold capacity from plants whose marginal costs are closer to the expected market clearing price. Indeed, the incentive to exercise market power with these units is increasing in the amount of inframarginal capacity that the company has. In future work it would be interesting to examine this behavior explicitly. It is worth emphasizing, however, that regardless of whether or not a company withholds output from its marginal plants, it still will make sense for the company to continue to operate its nuclear plants as much as possible.

3 Data and Empirical Strategy

3.1 Graphical Analysis

This study is conducted using the most comprehensive dataset ever compiled on the operating efficiency of U.S. nuclear power reactors. We constructed the primary dataset using the U.S. Department of Energy's *Power Plant Report*. We also put considerable effort into constructing detailed histories of the companies that own and operate nuclear reactors, identifying divestitures as the first month in which a reactor changes its status from utility to nonutility. These same data were also used to describe industry consolidation. The compiled dataset, detailed in the online data appendix, provides a complete record of monthly generation for all reactors from 1970 to 2009. We include in the main analysis all U.S. nuclear power reactors that were operating as of January 1, 2000. Later in the paper we also use data from the U.S. NRC's *Power Reactor Status Reports*. These data are available for a shorter time period (1999-2009), but provide *daily* operating status.

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%.¹⁰ 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). 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 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, such that 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 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

¹⁰ The most commonly reported measure of nuclear operating efficiency is the capacity factor, calculated as the ratio of net generation to maximum potential generation. The important difference between capacity factor and our measure is that reactor design capacity does not change over time whereas maximum potential generation may change over the lifetime of a reactor. Consequently, our measure reflects both the intensity with which the reactor is used and changes over time in maximum potential generation. Later in the paper we examine these two components separately.

and this dip in efficiency can be explained by several extended outages. During 1996, 1997, and 1998, ten reactors experience 12+ month outages, and seven of these were subsequently divested. One might be concerned that operators overhauled these reactors during the outages, potentially leading to improved long-run operating efficiency even in the absence of divestiture. We show later in the paper, however, that results are similar excluding reactors that experienced long outages. For the main results it is important to use all observations including these periods of unusually poor operating efficiency. Divestiture makes plant operators acutely aware of the financial cost of outages and independent power producers have incentive to go to great lengths to reduce their length and likelihood of occurring.

Finally, the figure also raises 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 would 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.¹¹

3.2 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 at the divested reactors during the 2000s had they not been divested. Whether or not this counterfactual is

¹¹ In testimony before the New Jersey Board of Public Utilities in 2005, Exelon made the potentially self-serving argument that, “[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.”

reasonable depends on whether the groups are *ex ante* similar, in terms of both observable and unobservable characteristics. Table 1 compares divested reactors with all other reactors. Many of the characteristics are similar in the two groups. Reactor designs differ between the two groups, but both groups include reactors of both types and from all four manufacturers. The most striking difference between the two groups is their geographic location. 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.

Given the underlying differences between the two groups, we are careful to control for reactor characteristics in the analysis that follows. The core of our strategy is to emphasize within-reactor changes in efficiency over time, which allows us to control for time-invariant observable and unobservable reactor characteristics. Then in Section 4.4 we assess empirically whether selection bias or differential trends by reactor type could be influencing our estimates. We report results, for example, from alternative specifications which restrict the analysis to Census regions for which there is common support and which reweight the sample using propensity scores. The results from these robustness tests tend to be very similar to our baseline results, leading us to believe that, despite the underlying differences, the non-divested reactors provide a reasonably accurate counterfactual for how operating efficiency would have evolved in divested reactors in the absence of deregulation.

3.3 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,

$$Y_{it} = \beta_0 + \beta_1 1[Divested]_{it} + \beta_2 X_{it} + \delta_i + \omega_t + \varepsilon_{it}. \quad (3)$$

Here i indexes reactors and t indexes months, and in the baseline specification we include all reactor-month observations from the period 1970-2009, amounting to 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 $1[Divested]_{it}$, 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. 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}), reactor fixed effects (δ_i), and month-of-sample fixed effects (ω_t). Finally, the error term ε_{it} captures unobserved differences in efficiency across reactor-months.

Several existing studies estimate production functions or cost functions using data from power plants. See, for example, Christensen and Greene (1976), Kleit and Terrell (2001) and Knittel (2002). Although equation (3) is not a production function, we interpret β_1 as a measure of efficiency gains. Our dependent variable is a measure of output much like what has been used in these previous studies. Where our estimation equation differs from previous work is that we do not explicitly include inputs. By far the most important input for nuclear power production is the capital embodied in the plant itself. Capital costs represent about 80% of the total cost of nuclear power, compared to, for example, only 15% for natural gas generation (Joskow and Parsons, 2009). The reactor fixed effects control for these time-invariant differences in capital inputs across reactors. Moreover, the month-of-sample fixed effects control for industry-wide changes in nuclear production (e.g., due to increased automation). Thus while we do not explicitly model reactor output as a function of inputs, these fixed effects control for important variation in inputs, implying that the divestiture-related changes we estimate reflect efficiency improvements. In particular, β_1 measures how far the utility owners were from the production frontier, which we define based on the production of the nonutility owners.

After the plant itself, the other important inputs for nuclear power production are fuel and labor, each accounting for about 10% of the total cost of nuclear power.¹²

¹² Du and Parsons (2009), Table 6C, reports the valuation of cost cash flows at a nuclear power plant by project year and expenditure category. As a percent of total project cost the largest category is construction cost (72%), followed by labor and other non-fuel operations and maintenance costs (11%), fuel and waste fees (10%), and incremental capital costs (7%). Plant-level data on incremental capital costs are not available after divestitures. An important exception are

Neither fuel nor labor consumption are observed at the plant-level in the United States after the divestitures. In our analysis, industry-wide changes in these inputs are controlled for with the month-of-sample fixed effects, and time-invariant cross-plant differences are captured with the reactor fixed effects. Divestiture creates incentives for firms to increase output and decrease costs along all margins, including labor and fuel efficiency, so there may have been time-varying, reactor-specific changes in these inputs. Thus, if anything, we are likely underestimating the gains from divestiture by not controlling for reactor-level variation in inputs. Aggregate data for uranium fuel consumption suggests that there has not been a substantial change in efficiency along this margin. Between 1994 and 2009 total uranium fuel consumption and total nuclear electric generation increased at very similar rates.¹³

The available evidence for plant employment suggests that there may have been a modest increase in labor efficiency, but that it is small compared to the approximately \$2.5 billion in additional revenue annually from increased output. We do not have a large enough sample to perform a rigorous statistical analysis, but for seven divested plants that we can follow from 1998 to 2002, average employment dropped by 20 percent, while at 24 non-divested plants for which we have comparable data, average employment dropped by 7.5 percent.¹⁴ This differential improvement in labor efficiency is consistent with existing evidence of modest labor reductions after divestiture at fossil-fuel-fired plants (Shanefelter 2008). Combining this with national-level data on salaries allows us to approximate the total change in labor expenditures. In 2009, the industry employed 62,000 workers at a total cost of \$6.4 billion (slightly more than \$100,000 annually per worker in wages, including bonuses). The plants in our sample employed roughly 800 workers each in the later part of our sample period, so if divested owners reduced their

investments undertaken to increase the capacity of a plant. The timing of these so called "uprates" are observed and we examine them explicitly in Section 5.

¹³ 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 billion kilowatt hours to 799 billion kilowatt hours.

¹⁴ The Federal Energy Regulatory Commission (FERC) collects and reports the average employment per year at plants owned by investor-owned utilities, but not at plants owned by independent power producers, making it impossible to use FERC data for such an analysis. Fortunately, during 2001 and 2002 the Department of Energy collected employment information for a subset of U.S. nuclear plants and we have been able to obtain those data and match them with average annual employment from the FERC Form 1.

annual wage bill by 15% more than the utilities, they would save roughly \$12 million dollars. Given that the average plant has two reactors, this aggregates up to about \$300 million annually in savings across all divested reactors.

4 Main Results

4.1 The Effect of Divestiture on Nuclear Operating Efficiency

Table 2 reports baseline estimates of the effect of divestiture on operating efficiency. Estimated coefficients and standard errors corresponding to $1[Divested]_{it}$ are reported from five separate regressions. The dependent variable in all regressions is net generation as a percent of design capacity. Controlling only for month-of-sample 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. The increase over the coefficient reported in column (1) 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 in Section 5, most of the variation in efficiency comes from reactor outages. The month-of-sample fixed effects capture, for example, that reactor outages tend to peak during particular months of the year, but the low R^2 reflects the fact that neither the month-of-sample fixed effects nor any other covariate is particularly effective at predicting the exact month in which an outage will occur for a particular reactor.

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.¹⁵ In

¹⁵ In calculating the size of the nuclear power market we assumed an average wholesale price of \$60 per megawatt hour. U.S. Department of Energy, Energy Information Administration, “Wholesale Market Data from Intercontinental

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.¹⁶ This is \$2.5 billion dollars worth of power annually, almost enough power to meet electricity demand for all the households in New England.¹⁷

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.¹⁸ Using a conservative estimate for the social cost of carbon dioxide (\$20 per ton) this implies an additional \$760 million in benefits annually.¹⁹ To put this into perspective, we are finding that the *increase* in electricity production associated with divestiture is more than *all* the electricity produced by U.S. wind and solar generation combined over this period.²⁰ This reflects, in part, the fact that there was little U.S. wind and solar generation until the end of the 2000s. However, it also makes the point that even modest improvements in operating efficiency can have substantial environmental implications when that

Exchange” reports daily average wholesale prices for six major trading hubs. Over the period 2001-2009 the average wholesale price was \$61.00.

¹⁶ 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 $(.102)(46,649)(24 \text{ hours/day})(365 \text{ days/year})(1000 \text{ kilowatts/megawatt}) = 42 \text{ billion kilowatt hours}$.

¹⁷ 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.

¹⁸ 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 $(2.48)(42)(1,000,000)/(2.73) = 38 \text{ million metric tons of carbon dioxide emissions}$. In practice increased nuclear production will displace whatever form of power production is *marginal* in a particular market during a particular day and hour. However, modeling all the different wholesale markets in the United States at an hourly level during this 10+ year period since deregulation goes beyond the scope of the analysis.

¹⁹ Federal Intergovernmental 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.

²⁰ 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 $(.102)(36,517)(24 \text{ hours/day})(365 \text{ days/year})(1000 \text{ kilowatts/megawatt}) = 32 \text{ billion kilowatt hours annually}$.

technology makes up a large share of the total market.

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. 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 at divested plants has actually declined relative to utility plants. Storing the additional spent uranium fuel creates additional costs. It is difficult to quantify the external costs of the additional spent fuel but available estimates in the literature indicate that the *private* costs of storage are small.²¹ Finally, companies with substantial inframarginal generating capacity, including nuclear reactors, find it more profitable to exercise market power. 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.

4.2 Heterogeneous Effects

Table 3 reports estimates from four separate regressions which describe the effect of divestiture by reactor type, reactor manufacturer, reactor vintage, and type of sale. In each case the indicator variable $1[Divested]_{it}$ is interacted with indicator variables for the different categories as listed in the row headings. The estimated coefficients on these interaction terms are positive in all eleven cases and statistically significant at the 1% level in ten out of eleven cases. In none of the four regressions can one reject the null hypothesis of equal coefficients. The uniformity of the results within and across columns indicates that the efficiency gains were experienced broadly across different types of reactors.

²¹ 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. 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 implies \$11 million in additional costs annually. See Idaho National Laboratory, *Advanced Fuel Cycle Cost Basis* INL/EXT-07-12107, Module E2 “Dry Storage of Spent Nuclear Fuel”.

The regression in column (4) tests whether efficiency gains differed depending on the type of sale. Of the 48 total divestitures, 19 (40%) were external sales in which reactors were sold to the highest bidder. With the other 29 divestitures, reactors were sold to independent power producers that were affiliated with the original owners. One might have expected external sales to lead to increased efficiency gains due to superior matching of operators to reactors. The results in column (4) provide some suggestive evidence for this hypothesis, but the point estimates for both types of sales are large, positive, and statistically significant.

Figure 2 plots point estimates and 95th percentile confidence intervals from 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. As we discuss later, 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.

4.3 The Effect of Consolidation on Nuclear Operating Efficiency

In addition to transferring operation of many reactors from companies subject to traditional cost-of-service regulation to independent power producers, 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.²²

Figure 3 describes consolidation in U.S. nuclear power operation over the period 1970-2009. We calculate for each reactor-month the number of other reactors operated by each reactor operator. The figure plots annual means of this variable separately for those reactors that were divested 1999-2007 and all other reactors. The figure illustrates how

²² See, for example, Joskow (1982), “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.”

divestitures have led to an unprecedented degree of consolidation in the industry. As late as the mid-1990s, there was relatively little consolidation. The average reactor was operated by a company that operated fewer 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 one-third of all U.S. nuclear capacity.

In principle, consolidation could improve operating efficiency in several ways. Whereas a utility with a single reactor must 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."²³ Also, within a consolidated company, employees can disseminate best practices for refueling and maintenance.²⁴ These effects are in addition to incentives created by a divestiture, in which the operator, regardless of 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

²³ 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 purchased several plants in the United States including Clinton and Three Mile Island 1 through a joint venture with *Amergen*.

²⁴ 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 conference call for discussing potential problems and managers at FirstEnergy travel from plant to plant.

are several reactors that are operated by companies that control both divested and cost-of-service regulated, utility reactors.

Table 4 reports regression estimates. Column (1) presents the baseline estimate, identical to the third column in Table 2. In column (2), we expand the estimating equation to include our consolidation variable. The coefficient estimate on consolidation is 0.48, implying that increasing by one the number of other reactors operated by the same operator improves efficiency by about half a percentage point.²⁵ Although the coefficient is estimated with some noise (p -value 0.09), the point estimate is large enough to be economically important. 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 $1[Divested]_{it}$.

Columns (3) and (4) report results from alternative specifications using narrower measures of consolidation. One might have expected economies-of-scale in operation to be particularly large for companies that own multiple reactors of the same type (pressurized water versus boiling water) or manufactured by the same firm. Accordingly, in these specifications consolidation is measured using only reactors of the same type or manufacturer, respectively. The point estimates are similar to the point estimate in column (2) suggesting that the gains from consolidation come from broad changes in operations, rather than from specific changes related to the technical characteristics of particular reactor designs.²⁶ It is difficult to draw strong conclusions, however, because the parameter estimates are again 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, as depicted in Figure 3. In column (5) we re-estimate the specification reported in

²⁵ In alternative results not reported we tested for nonlinear effects by including a squared 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.

²⁶ In related work, Lester and McCabe (1993) compare operating efficiency of U.S. and French nuclear reactors. In contrast to the U.S. experience, France early on adopted a single reactor design for all commercial reactors. Lester and McCabe argue that this standardization has increased learning-by-doing in plant operation and test empirically for differential learning among reactors of different designs.

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. 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 statistically significant at the two percent level (p -value 0.013).²⁷

In additional unreported results we also considered a number of specifications aimed at assessing potential *interactions* between divestiture and consolidation. When we include an interaction term between divestiture and consolidation the point estimates on both the interacted and uninteracted consolidation terms are positive but neither are statistically significant. We also tested for a change in operating efficiency among non-divested reactors when reactors operated by the same company are divested. If there are spillovers within companies then one might have expected an increase in operating efficiency among these reactors. On the other hand, if companies are able to shift resources, such as skilled operators, between divested and non-divested reactors, then one might have expected a decrease in operating efficiency. In the regression the estimated effect of divestiture on non-divested reactors is small and not statistically significant, providing no evidence for either hypothesis. However, there are only nine non-divested reactors operated by companies that operate at least one divested reactor so these results are too imprecisely estimated to draw strong conclusions.

²⁷ 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.”

Much of the consolidation in the U.S. nuclear industry has occurred through the growth of particular companies, including Exelon and Entergy. Although the results in Table 4 are consistent with economies of scale, it could also be that there is persistent heterogeneity in management quality across companies and that divestiture has reallocated plants to companies with more effective managers. In alternative, unreported results we include indicator variables for Exelon, Entergy, and NextEra (the three companies that own the most U.S. reactors as of 2009).²⁸ The estimated coefficient corresponding to divestiture remains large and highly statistically significant. The point estimate on consolidation is essentially unchanged but the standard error grows considerably.

Overall the results provide some mild evidence of 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, indicating that it is divestiture and not consolidation driving the large share of the efficiency gains.

4.4 Considering Possible Concerns about Selection Bias

This subsection evaluates potential concerns about selection bias and differential trends in operating efficiency. From the mean characteristics reported in Table 1 it is clear that the divested reactors differ from the non-divested reactors in several ways. Our preferred specifications include reactor fixed effects which control for observed and unobserved differences between reactors. Still, one could be concerned that the reactors that were divested had different pre-existing trends, or were somehow selected based on unobservable characteristics that were changing over time. Although it is impossible to completely rule out these concerns, there are several features about how deregulation

²⁸ Interestingly, prior to deregulation there is little evidence that these companies were the best-managed. The three largest U.S. nuclear companies as of 2009 are Exelon (formerly Commonwealth Edison), Entergy, and NextEra (formerly FPL Group). Between 1990 and 1998, reactors owned by these three companies had *lower* operating efficiency on average than other U.S. reactors.

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 5.

Second, with the exception of Michigan, all nuclear reactors were divested in states where deregulation occurred. 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 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.²⁹ 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 $1[Divested]_{it}$ 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

²⁹ California is also an interesting case because it was one of the states that experimented with incentive regulation during the late 1980s and early 1990s. Throughout the analysis, the comparison group in our regressions includes nuclear plants subject to traditional cost-of-service regulation as well as plants operating under different forms of incentive regulation. Sappington (2001) identifies 16 states in which electric utilities were operating as of 2001 under some form of incentive regulation. Only 10 of the states have nuclear reactors. When we reestimate the model using as a comparison group only reactors operating in these 10 states the estimate is 10.1 (3.0), consistent with the existing literature that finds little robust evidence that incentive regulation increases operating efficiency.

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 2001 as the divestiture date for all divested reactors, the estimated coefficient on $1[Divested]_{it}$ is smaller (consistent with attenuation bias), but still positive and statistically significant. See column (4).

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 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 (see, e.g., White 1996). Differences in electricity rates across states have much more to do with the *type* of generating equipment in each state's generation portfolio, rather than the *efficiency* with which it is operated. 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. Columns (5) and (6) present additional robustness tests, excluding from the regression all reactors in the Northeast and weighting never-divested reactors using propensity weights.³⁰ Point estimates in these specifications are again very similar. Both specifications are demanding tests of the data which require excluding more than half of the divested reactors from the sample and the fact that the point estimates are again positive and statistically significant at the 1% level provides additional evidence that the observed efficiency gains are not driven by selection.

The specifications described in columns (7)-(10) 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.

Finally, column (11) addresses potential bias related to plant closures during the 1990s. Between 1993 and 1997, five full-scale (100 megawatt+) commercial reactors were closed, all located in states that subsequently deregulated their electricity markets and divested nuclear plants. It is possible that impending divestitures encouraged owners

³⁰ The idea of propensity score weighting is to reweight the observations in the comparison group to balance the mean characteristics of divested reactors. Propensity scores were estimated using a logit regression where the dependent variable is an indicator variable for reactors that were ever divested. Regressors include mean design capacity, reactor age, and indicators for reactor type, manufacturer, and census region. This specification necessarily excludes all reactors in the Northeast census region where all reactors were divested as well as all reactors in the West census region where none of the reactors were divested.

to close plants at which they expected performance to degrade while comparable plants in non-divesting states remained open. Over their lives, the five closed plants did not have particularly low output. In fact, their average through 1990 was slightly higher than all divested reactors, but they were distinctly worse (six percentage points) than divested reactors in the first half of 1990s. To bound the possible bias introduced by the closure of these five reactors, we matched them with reactors of similar vintage and size that were not divested. We then calculated changes in net output from the fifteen years before the closure to the fifteen years after for the matched sample, and used those changes to impute post-closure output from the five reactors based on their fifteen-year average net output before the close. These estimates, therefore, reflect what would have happened to the plants had they been operated similarly to the plants of comparable vintage and size in states that did not divest. The coefficient on $I[Divested]_{it}$ declines slightly to 8.6 percentage points, suggesting that the decisions to close reactors, even if related to the impending divestitures, likely does not explain much of the estimated effect.

5 Understanding the Mechanisms behind Post-Divestiture Gains

We next turn to ancillary evidence aimed at understanding the *mechanisms* driving this observed increase in operating efficiency. Table 6 reports coefficient estimates corresponding to $I[Divested]_{it}$ for seven alternative dependent variables. Regression coefficients are reported for three different specifications which add control variables as one moves from left to right.

Panel (A) examines whether divested reactors have been more likely to increase their maximum generating capacity. U.S. nuclear power reactors are licensed to operate at a maximum heat level but plant operators can petition to increase this capacity in what is known as an “uprate.” Since 1970 nuclear uprates in the United States have added 6,000 megawatts of total electric capacity -- the equivalent of 6 new 1000 megawatt reactors.³¹ Controlling for reactor fixed effects and reactor age, divestiture is associated

³¹ Modest uprates (2-3%) can be performed with little or no equipment replacement, but larger uprates typically require modifications to non-nuclear equipment such as high-pressure turbines, condensate extraction pumps, motors, and transformers. According to “New Plant from Old,” *Nuclear Engineering International*, September 12, 2005, the cost of these modifications ranges from \$750 to \$900 per kilowatt of added capacity. Thus, a large (e.g. 8%) uprate for the

with an increase of 1.7-1.9 percentage points, although the coefficients are not statistically significant.

Figure 4 performs an analogous graphical analysis, plotting mean licensed thermal capacity for divested and non-divested reactors as a percent of the original license. During the early 1970s all reactors operated at their original licensed capacities. Uprates increase sharply beginning around 2000 and it appears that capacity increases differentially for independent power producers. Viewed together with the regression estimates this provides suggestive evidence of a relationship between divestiture and increases in generating capacity.

Panel (B1) focuses on reactor operating days and shutdowns. In the 1999-2009 period for which daily data are available, reactors are operating during 91% of all days. With the full set of controls divestiture is associated with an increase of 3.8 percentage points. This is large relative to the mean, implying 13-14 additional operating days per year per reactor. Figure 5 provides a complementary graphical analysis, plotting the fraction of reactors not operating by day of year. Outages peak twice annually, once during the spring and again once in the fall. At the beginning of the sample the annual pattern for divested and non-divested reactors is similar but by the end of the sample outages are considerably less frequent among divested reactors. This holds for almost all days of the year, with particularly large differences during the late spring and late fall.

Although they represent a small share of total outages, automatic shutdowns or “scrams” are particularly interesting because they are a measure of reactor safety. All three point estimates in this row are negative. The coefficients in the second and third columns are not statistically different from zero (p -value .09 for both), but are estimated with enough precision to reject increases larger than 5%.³² Moreover, these 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

median-sized reactor in our sample (794 megawatt) could cost \$50-\$60 million. Although not negligible, this is small compared to the value of the increased electrical generation and tiny compared to the cost of building a new nuclear reactor.

³² Hausman (2011) finds similar results examining a variety of different safety measures including “initiating events” of which scrams are a subset.

are complementarities between safety and operating efficiency.³³ 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. In the third column, divestiture is associated with an 8% decrease in the number of outages per year, and a 36% decrease in the mean outage length, but neither are statistically significant. The lack of precision makes it impossible to make definitive statements but it appears that outage length is the more important of the two.

Finally, Panel (C) examines capacity factor among operating reactors. With the full set of controls the estimates are small in magnitude and not statistically significant. This is consistent with a graphical analysis (see Figure 6) which shows that mean capacity factor by day of year is very similar for divested and non-divested reactors during the post-divestiture period. While divested reactors appear to have fewer outages and operate at higher maximum capacity, *during operation* they do not appear to be operating at a higher capacity factor. This reflects the fact that, when operating, nuclear reactors are typically run at full power.

6 Conclusion

This paper examines an unprecedented period of deregulation and consolidation in the U.S. nuclear power industry. We analyze operating efficiency 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

³³ 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.

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 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 remains an important priority for future work.

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

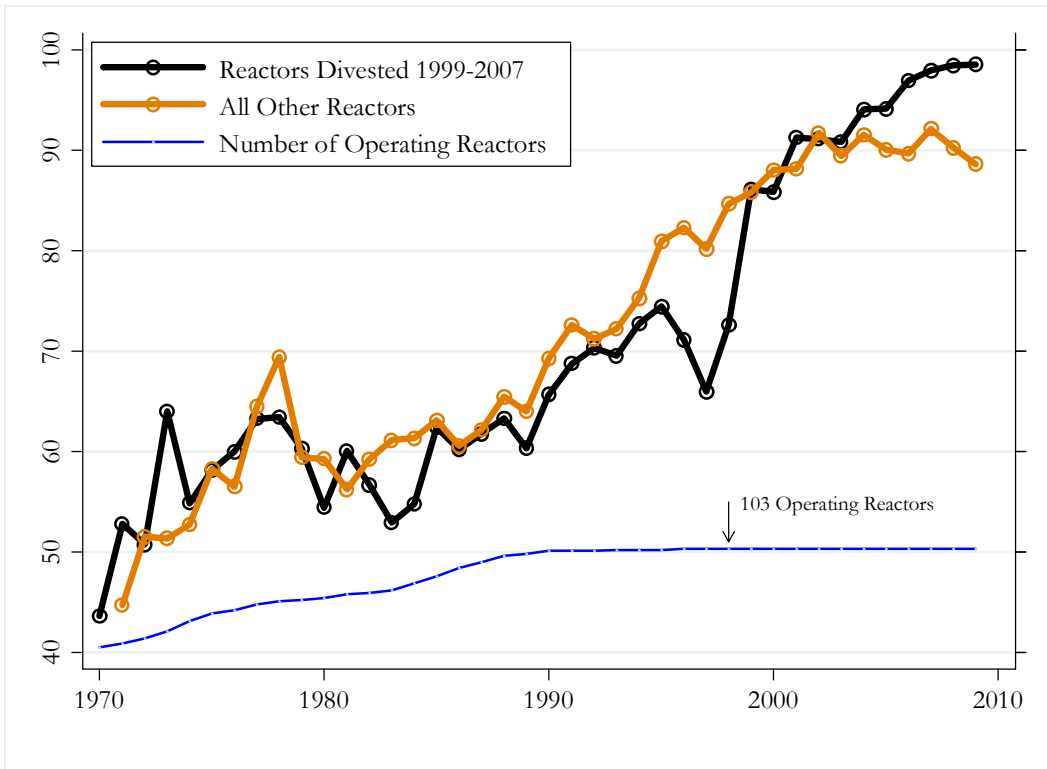


Figure 2: The Effect of Divestiture on Operating Efficiency by Month of Year

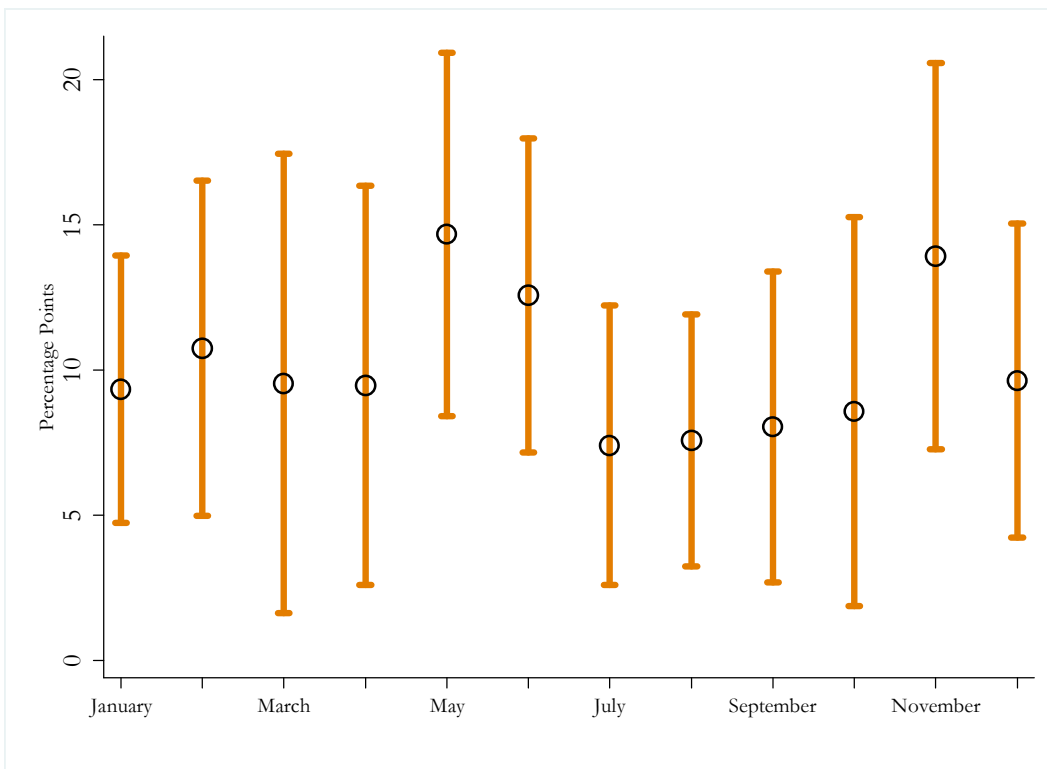


Figure 3: Number of Reactors Operated by the Same Operator, 1970-2009

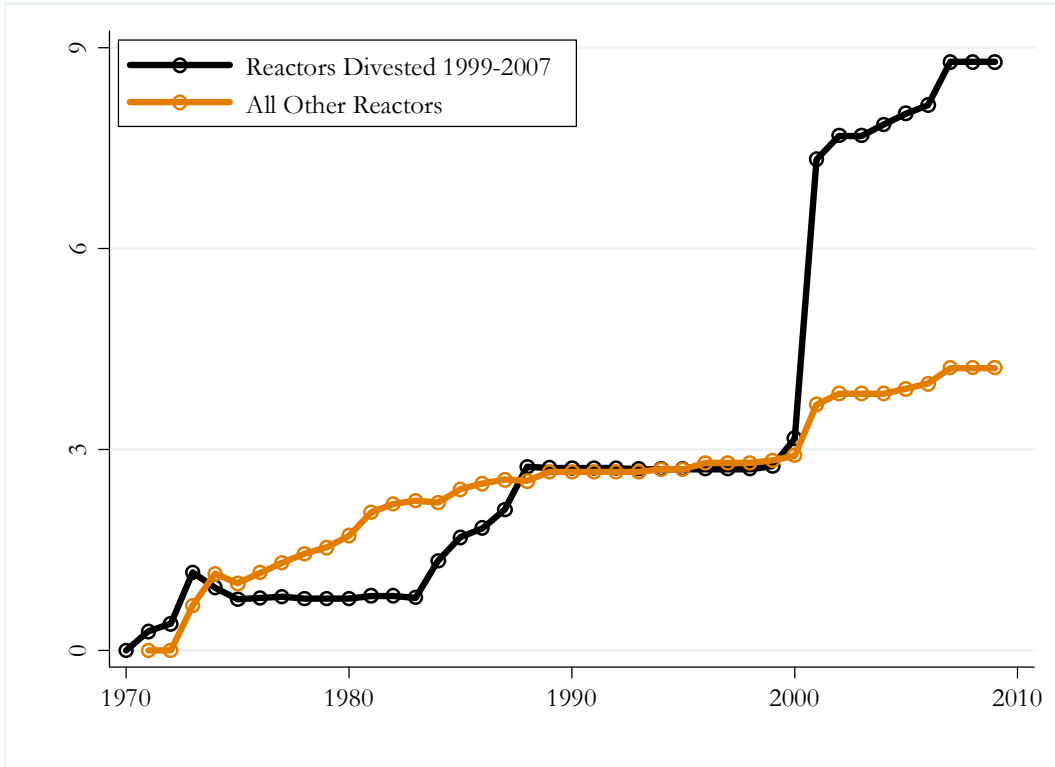


Figure 4: Licensed Thermal Capacity as a Percent of Original License, 1970-2009

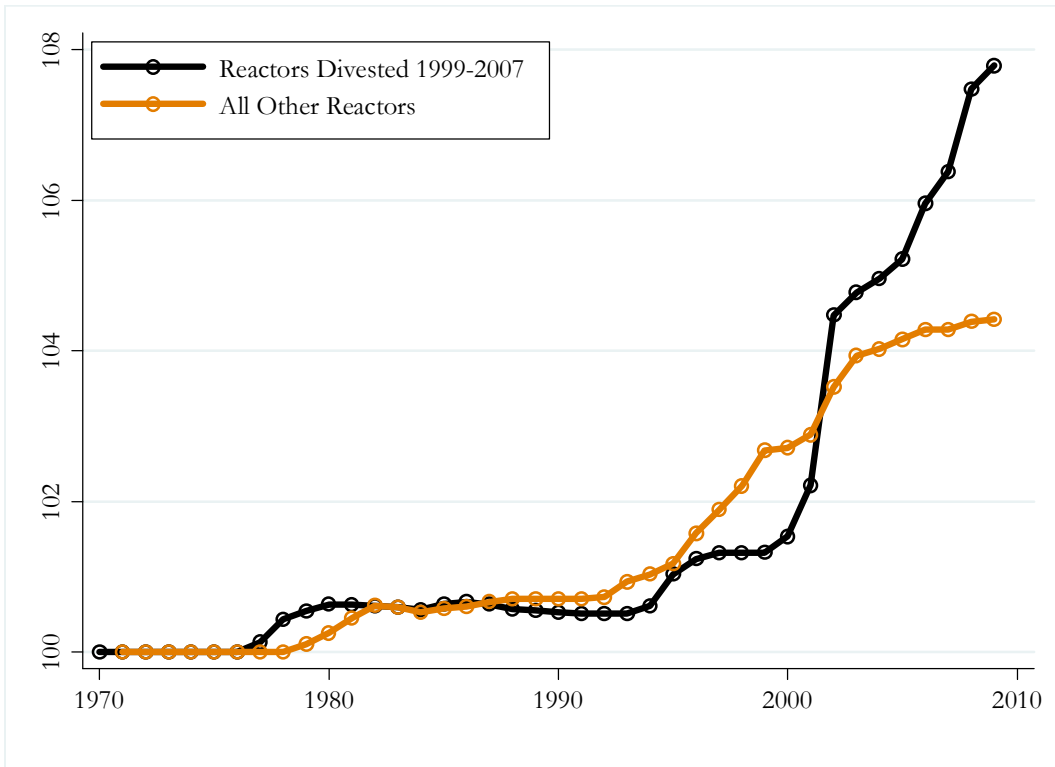


Figure 5: Fraction of Reactors Not Operating By Day of Year

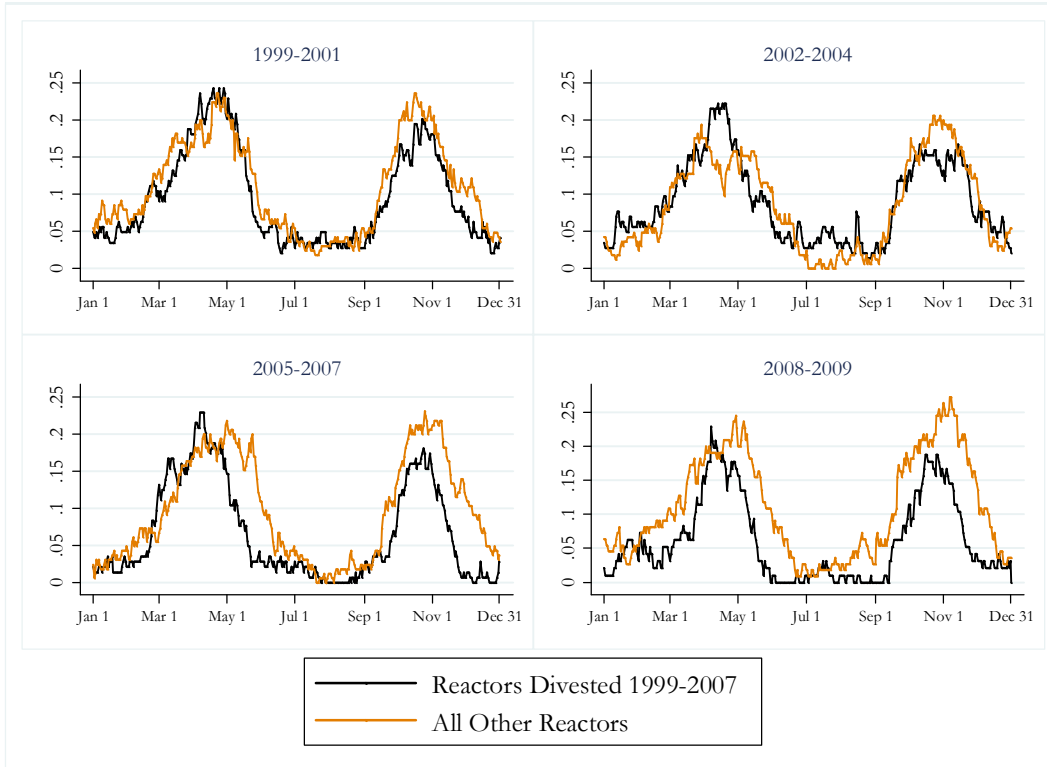


Figure 6: Mean Capacity Factor by Day of Year for Operating Reactors, 2005-2009

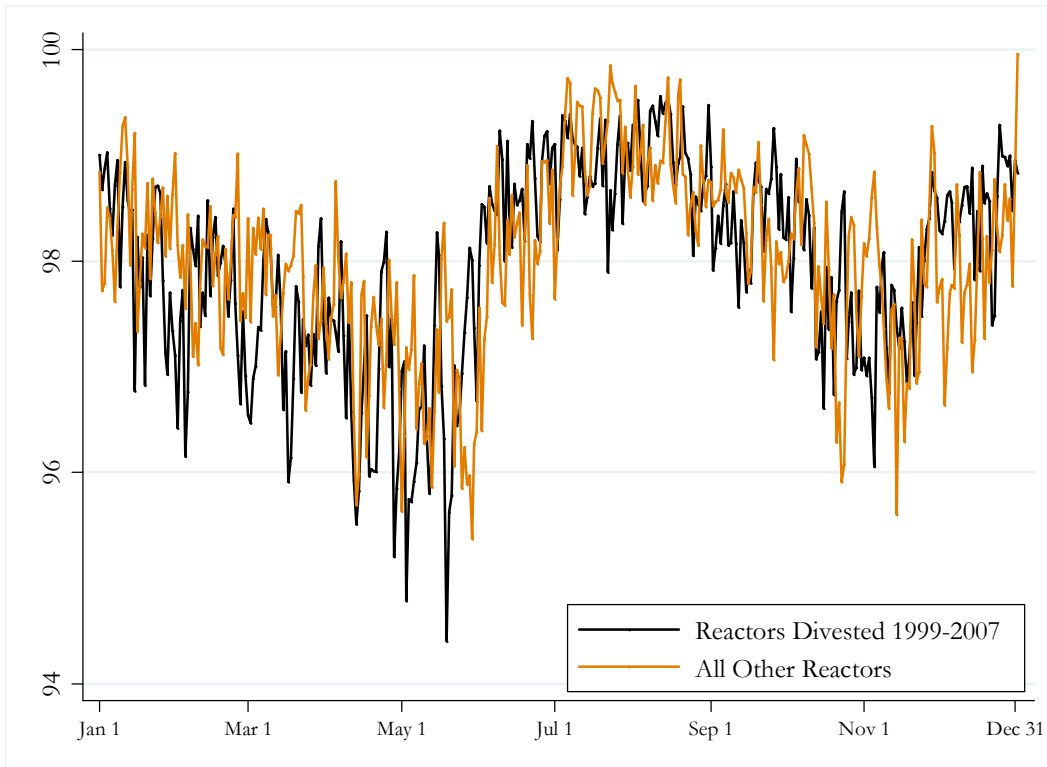


TABLE 1
Comparing Divested With Non-Divested Nuclear Reactors

	(1)	(2)	(3)
	Reactors Divested 1999-2007 (n=48)	All Other Reactors (n=55)	<i>p</i> -value (1) vs (2)
Mean Reactor Characteristics			
Design Capacity (in MWe)	921.9	959.7	.38
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			
Pressurized Water Reactor	54%	78%	.01
Boiling Water Reactor	46%	22%	.01
Reactor Manufacturer			
Westinghouse	42%	51%	.35
General Electric	46%	22%	.01
Combustion Engineering	8%	18%	.15
Babcock and Wilcox	4%	9%	.33
Reactor Location			
Northeast Census Region	50%	0%	.00
Midwest Census Region	38%	18%	.03
South Census Region	13%	67%	.00
West Census Region	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 2
The Effect of Divestiture on Nuclear Operating Efficiency

	(1)	(2)	(3)	(4)	(5)
$1[Divested]_{it}$	6.5** (1.2)	10.4** (2.1)	10.2** (2.0)	10.2** (2.0)	9.7** (2.0)
Month-of-Sample Fixed Effects (480 months)	Yes	Yes	Yes	Yes	Yes
Reactor Fixed Effects (103 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	23,796
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 3
The Effect of Divestiture By Reactor Design, Manufacturer, Vintage, and Type of Sale

	(1) By Reactor Type	(2) By Reactor Manufacturer	(3) By Reactor Vintage	(4) By Type of Sale
Pressurized Water Reactors (n=22)	9.5** (2.5)			
Boiling Water Reactors (n=26)	10.8** (2.7)			
Westinghouse (n=20)		10.0** (2.9)		
General Electric (n=22)		10.8** (2.7)		
Combustion Engineering (n=4)		5.9 (3.4)		
Babcock and Wilcox (n=2)		12.5** (1.9)		
Completed Before 1975 (n=17)			10.3** (2.7)	
Completed 1975 - 1985 (n=13)			13.7** (3.6)	
Completed After 1985 (n=18)			7.2** (2.6)	
External Sales (n=19)				11.5** (2.8)
Internal Sales (n=29)				9.4** (2.3)
Month-of-Sample Fixed Effects (480 months)	Yes	Yes	Yes	Yes
Reactor Fixed Effects (103 reactors)	Yes	Yes	Yes	Yes
Reactor Age (cubic)	Yes	Yes	Yes	Yes
Number of Observations	36,667	36,667	36,667	36,667
R ²	.22	.22	.22	.22

Notes: This table reports coefficient estimates and standard errors from four 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 four regressions is it possible to reject the null hypothesis that the estimated coefficients are equal. The *p*-values from the tests of equal coefficients are .68, .12, .31, and .51, respectively.

TABLE 4
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)	<i>Excluding Divested Reactors</i>	6.5** (2.1)
Number of Reactors/Plants Operated by the Same Operator	--	.48 (.28)	--	--	.87* (.34)	.98* (.38)
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-of-Sample Fixed Effects (480 months)	Yes	Yes	Yes	Yes	Yes	Yes
Reactor/Plant Fixed Effects (103 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 six 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 (5) 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 5
 Considering Possible Concerns About Selection Bias, Long Outages, and Closures

	Selection Bias						Long Outages 1996-1998				Closures
	(1) Excluding Michigan	(2) Excluding California	(3) Excluding Iowa and Wisconsin	(4) Divest Date 1/2001 For All Reactors	(5) Excluding the Northeast Census Region	(6) Propensity Score Weighting	(7) Excluding Years 1996- 1998	(8) Excluding 12+ Month Outages 1996-1998	(9) Excluding Reactors With 12+ Month Outages 1996-1998	(10) Including Indicator Variables for All 12+ Month Outages, During and After	(11) Including Five Closed Reactors with Imputed Post-Close Operations
$1[Divested]_{it}$	9.7** (2.0)	10.4** (2.1)	10.3** (2.1)	7.9** (2.4)	10.0** (2.6)	11.0** (3.1)	8.8** (2.0)	9.1** (2.1)	8.2** (1.9)	7.4** (1.5)	8.6** (1.7)
Month-of-Sample Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reactor Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reactor Age (cubic)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of Reactors	99	99	99	103	79	71	103	103	93	103	108
Number of Observations	35,459	35,155	34,905	36,667	27,825	25,484	32,963	36,452	33,177	36,667	38,705
R ²	.23	.22	.23	.22	.21	.22	.24	.22	.23	.34	.22

Notes: This table reports coefficient estimates and standard errors corresponding to an indicator variable for reactors that have been divested from eleven 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 (10) 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. Column (11) includes observations from the five reactors in divesting states closed between 1993 and 1997 with imputed values after their close date. Standard errors are clustered at the plant level. Single and double asterisks denote statistical significance at the 5% and 1% level.

TABLE 6
Understanding the Mechanisms behind Post-Divestiture Gains

	(1)	(2)	(3)
A. Maximum Generating Capacity			
Maximum Generation Over Last 12 Operating Months [Sample Mean: 100.4]	2.5** (0.9)	1.6 (1.5)	1.7 (1.4)
Maximum Licensed Thermal Capacity (MW _t) [Sample Mean: 102.0]	1.9 (1.1)	2.0 (1.1)	1.9 (1.1)
B1. Operating Days and Shutdowns			
1[<i>Operating</i>] _{it} x 100 [Sample Mean: 91.0]	3.9** (0.7)	3.5 (2.0)	3.8* (1.9)
1[<i>Scram</i>] _{it} x 100 [Sample Mean: 0.2]	-.01 (.02)	-.06 (.04)	-.06 (.04)
B2. Length Versus Number of Outages			
Number of Outages per Year [Sample Mean: 1.7]	-.17 (.11)	-.13 (.16)	-.13 (.16)
Mean Outage Length in Days [Sample Mean: 19.1]	-6.4** (1.3)	-6.2 (5.4)	-6.9 (5.3)
C. Capacity Factor when Operating			
Capacity Factor in Percent Excluding Zeros [Sample Mean: 97.7]	-0.3 (0.3)	0.5 (0.3)	0.4 (0.3)
Time Effects (4,017 days / 11 years)	Yes	Yes	Yes
Reactor Fixed Effects (103 reactors)	No	Yes	Yes
Reactor 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 21 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.

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

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August 2011

This study is conducted using the most comprehensive dataset ever compiled on the operating efficiency of U.S. nuclear power reactors. Our primary dataset describes 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 (see Section 4.4 in the paper). We also put considerable effort 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 40-year monthly panel was constructed using data from the U.S. Department of Energy’s *Power Plant Report* (EIA-923).¹ The *Power Plant Report* is a monthly survey of operators of nuclear reactors and other large electric generating facilities that includes total electricity generation and other information.² The compiled dataset provides a complete record of monthly generation for

¹ Previous versions of the EIA-923 were the EIA-906 and EIA-759.

² 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.

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.³ 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.

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

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

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,

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

³ 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. This imputation is unlikely to bias our results because divestitures tend to occur at the same time for all reactors in multi-reactor plants. The one exception is Indian Point where prior to 2001 the plant's two active reactors had different owners. It turns out, however, that because of this ownership structure the *Power Plant Report* includes reactor-level generation for Indian Point for all years, making no imputation necessary.

When reactor design capacity is equal to maximum potential generation these two measures are identical. The important difference between (1) and (2) 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.⁴ We use the reactor design capacities reported in 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 contains information about reactor operators including whether the reactor operator is a utility or a nonutility. We use this information to construct an indicator variable for reactors that have been divested. We identify divestitures in the *Power Plant Report* as the first month in which a reactor changes its status from utility to nonutility.⁵ These same data were also used to describe industry consolidation. For each reactor and month observation we calculate the number of other reactors operated by that reactor’s operator.⁶ In cases where companies are subsidiaries of other companies we treat this as the same company. Where this is unclear we used SEC

⁴ 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.

⁵ See Appendix Table 2 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 non-utilities. 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.

⁶ 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.

filings to determine the ownership structure.⁷ 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.

We also use data from 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 operating data from 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."

Appendix 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 more than 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 manufacturers.⁸ In the paper we evaluate whether operating efficiency differs systematically across these different designs.

Panel B in Appendix Table 1 describes operating efficiency and outages. Mean net

⁷ 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.

⁸ 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. In our sample General Electric produced only boiling water reactors and the other three manufacturers produced only pressurized water reactors.

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 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.

ONLINE APPENDIX 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 Reactors	69
Boiling Water Reactors	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.

ONLINE APPENDIX 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)	
Percentage of Daily Observations at 100% Capacity Factor	77%
Percentage of Daily Observations at 90% - 99%	9%
Percentage of Daily Observations at 1% - 89%	4%
Percentage of Daily Observations at 0%	9%
Outages 1999-2009 (Nuclear Regulatory Commission)	
Percentage of Outage Days Manual Shutdown for Refueling	73%
Percentage of Outage Days Manual Shutdown for Other Reasons	24%
Percentage of Outage Days Automatic Shutdown ("scram")	2%

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*.

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ONLINE APPENDIX TABLE 2
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

ONLINE DATA APPENDIX

ONLINE APPENDIX TABLE 2 (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.