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Deregulation, Consolidation, and Efficiency: Evidence from US Nuclear Power†

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Beginning in the late 1990s, electricity markets in many US 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 US nuclear capacity. We find that deregulation and consolidation are associated with a 10 percent increase in operating performance, achieved primarily by reducing the duration of reactor outages. At average wholesale prices, this increased operating performance is worth $2.5 billion annually and implies an annual decrease of 35 million tons of carbon dioxide emissions. (*JEL* L11, L51, L94, L98, Q42, Q48)

This paper examines an unprecedented period of deregulation and consolidation in the US 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 performance. 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 US nuclear capacity.

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 performance, achieved primarily by reducing the frequency and, more importantly, duration of reactor outages. Gains in operating performance 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 gains across companies that operate different numbers of reactors. While we find suggestive evidence that consolidation led to improved operating performance, it explains relatively little of the overall increase.

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Our results imply a substantial increase in electricity production. In 2010, nuclear reactors produced 800 billion kilowatt hours of electricity, about 20 percent of total US electricity generation. We estimate that the increase in electricity production due to deregulation and consolidation exceeds 40 billion kilowatt hours annually. At current wholesale prices, the value of the increased electricity production is approximately $2.5 billion annually. In addition, because the increased electricity production displaces mostly coal- and natural gas-fired power, these gains have important implications for the environment, implying an annual decrease of 35 million metric tons of carbon dioxide emissions. To put this into perspective, this is more carbon abatement than was achieved by *all* the US 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.

Before concluding that the increase in operating performance reflects an efficiency gain, we examine plant-level evidence on capital investments, employment, and salaries, as well as aggregate evidence on nuclear fuel consumption and the storage of spent nuclear fuel. We find that expenditure on some of these inputs tends to increase, but that the total increase in expenditures is small compared to the $2.5 billion in increased annual revenue.

More difficult to quantify are external costs associated with possible changes in the risk of nuclear accidents. Some have argued that deregulation would lead to a decrease in safety as independent power producers cut corners in an attempt to increase short-term returns. Others have made the counterargument that safety and operating performance are complements, and that emphasizing safety is particularly good business for deregulated companies whose main business is operating nuclear power plants, as an accident would create negative spillovers to their other plants. We find that divestiture and consolidation are associated with a *decrease* in the number of emergency reactor shutdowns. The point estimate is relatively noisy (p-value 0.09), but is estimated with enough precision to reject increases larger than 5 percent. Although we view these results as suggestive, we also explain that emergency shutdowns are an imperfect measure of safety. As more and richer data become available, it will be important to revisit this central issue.

The US nuclear power industry is a particularly good candidate for an empirical study of operating performance. 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 performance is unlikely to be confounded by unmodeled changes in demand.[1] Third, during the relevant period, there is very little entry or exit of nuclear reactors, mitigating concerns about selection that substantially complicate similar analyses (Olley and Pakes 1996). 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.

[1] 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.

The format of the paper is as follows. Section I provides background information about nuclear power and the broader electricity industry. Section II describes the data and empirical strategy. Section III includes the main results, presenting estimates of the effect of divestiture and consolidation on nuclear operating performance for a variety of different specifications including a set of regressions aimed at addressing potential concerns about selection bias, as well as additional results aimed at understanding the mechanisms driving the increase in performance. Section IV attempts to place the results in a broader context, presenting additional results on fuel, equipment, and labor expenditures, as well as performing an analogous analysis for our measure of reactor safety. Section V offers concluding comments.

I. Background

A. *Nuclear Power in the US Electricity Industry*

In the United States, electricity is generated using coal (45 percent); natural gas (24 percent); nuclear (20 percent); hydro (6 percent); and wind, solar, and other renewables (4 percent).[2] 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.[3] 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 start-up costs.

These features imply that nuclear reactors are typically used to provide base-load power, 24 hours a day. This explains why in the United States nuclear power accounts for only 10 percent of capacity but produces 20 percent of total electricity.[4] 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. Marginal costs for nuclear plants are low compared to wholesale prices, so nuclear operators strive to minimize planned and unplanned outages. From an empirical perspective, this is advantageous because it essentially eliminates concerns about changes in performance being correlated

[2] These shares are from 2010 according to the US Department of Energy, Energy Information Administration, *Annual Energy Review 2010*, released October 2011, Table 8.2a "Electricity Net Generation."

[3] Massachusetts Institute of Technology (MIT) (2009) reports fuel costs (per megawatt hour) of \$23 and \$48 for coal-fired 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.

[4] US Department of Energy, Energy Information Administration, *Annual Energy Review 2010*, released October 2011, Tables 8.11a "Electric Net Summer Capacity" and Table 8.2a "Electricity Net Generation." In 2010, nuclear power accounted for 9.7 percent of net summer capacity and 19.6 percent of total net generation.

with observed or unobserved changes in demand.[5] 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.[6]

Nuclear plants are very large, so even small improvements in operating performance imply substantial amounts of electricity. At typical wholesale electricity prices ($60 per MWh), a two-reactor 2,000 megawatt plant that operates 80 percent of the year produces power worth approximately $840 million annually. An increase from 80 percent to 85 percent increases revenues by $52 million annually, $120,000 for each additional hour that the plant is operating. Given the low marginal cost of nuclear generation, this is mostly profit.

B. *The Regulation and Deregulation of the US 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 performance. Poor operating performance 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 performance, 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

[5] 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." This highlights two distinct advantages of our study. We measure output directly and output should not be influenced by changes in demand conditions.

[6] There may be a second-order effect of demand- and supply-side factors on nuclear power operations since higher prices will make it even more profitable to keep the nuclear reactor online. Owners may invest more in ensuring that the reactor continues to operate if they face high prices. This effect appears to be small in practice. Below we present evidence that the gains from divestiture do not vary across reactors facing different wholesale prices. Moreover, we test for, but find no evidence of, reactor operators timing outages to match short-run price fluctuations.

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, deregulation 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 jump-start 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 in the period 2003–2010, and by the end of the decade 35 percent of US electricity capacity was controlled by independent power producers.[7] The timing of the nuclear plant divestitures followed the broader industry trend.

A number of empirical papers have evaluated the effects of US electricity restructuring, including its impact on the efficiency of wholesale power markets (Borenstein, Bushnell, and Wolak 2002; Bushnell, Mansur, and Saravia 2008; and Hortaçsu and Puller 2008), consumer responses to retail competition (Hortaçsu, 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 performance for 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

[7] Table 1.1a "Existing Net Summer Capacity by Energy Source and Producer Type" in US Department of Energy, Energy Information Administration, *Electric Power Annual 2010*, revised December 2011.

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 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 nonnuclear 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.

II. Data and Empirical Strategy

A. *Graphical Analysis*

This study is conducted using the most comprehensive dataset ever compiled on the operating performance of US nuclear power reactors. We constructed the primary dataset using the US 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 US nuclear power reactors that were operating as of January 1, 2000. Later in the paper we also use data from the US Nuclear Regulatory Commission'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 40-year period, from near 50 percent of reactor capacity to above 90 percent.[8] This industry-wide increase has been attributed

[8] The most commonly reported measure of nuclear operating performance 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

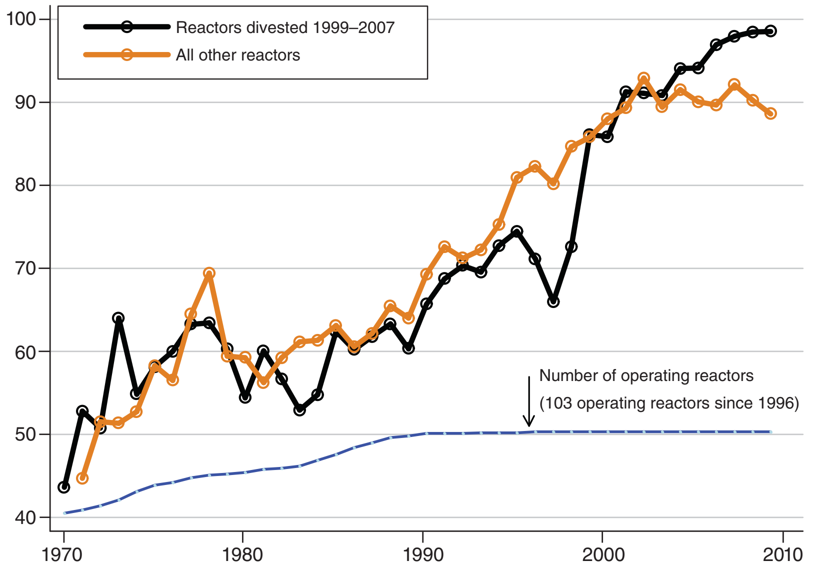

Figure 1. Net Generation Scaled by Reactor Design Capacity

Note: Thirty-six of the 48 divestitures occurred between 1999 and 2002.

in part 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, 161). 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 performance for divested reactors tracks reasonably closely the mean performance for all other reactors. During the 1980s and 1990s, performance for divested reactors tends to be somewhat lower than performance for all other reactors. Then, beginning in the late 1990s, performance for divested reactors increases, such that for every year between 2003 and 2009 the mean performance for divested reactors is higher than the mean performance for all other reactors. This period 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 performance 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 operating performance, while controlling for a number of potentially important confounding factors.

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.

It is also worth highlighting the pronounced dip in operating performance during the late 1990s among reactors that were subsequently divested. We have examined this period carefully, and this dip can be explained by several extended outages. During 1996, 1997, and 1998, 10 reactors experience 12+ month outages, and 7 of these were subsequently divested. One might be concerned that operators overhauled these reactors during the outages, potentially leading to improved long-run operating performance 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 performance. 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 nondivested 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 performance 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 nondivested reactors may provide some empirical support for that argument.[9]

B. *Covariate Balance*

The regression analysis described in the following sections is based on comparisons between divested and nondivested reactors, with the operating performance of nondivested 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 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 nondivested 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

[9] 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."

TABLE 1—COMPARING DIVESTED WITH NONDIVESTED NUCLEAR REACTORS

	Reactors Divested 1999–2007 ($n = 48$) (1)	All other reactors ($n = 55$) (2)	p-value (1) versus (2) (3)
Mean Reactor Characteristics			
Design capacity (in MWe)	921.9	959.7	0.38
Reactor age as of December 1998	18.8	18.4	0.74
Number of reactors operated by the same reactor operator as of December 1998	3.8	4.0	0.67
Reactor Type, share that are:			
Pressurized water reactor	0.54	0.78	0.01
Boiling water reactor	0.46	0.22	0.01
Reactor Manufacturer, share made by:			
Westinghouse	0.42	0.51	0.35
General Electric	0.46	0.22	0.01
Combustion Engineering	0.08	0.18	0.15
Babcock and Wilcox	0.04	0.09	0.33
Reactor Location, share in:			
Northeast census region	0.50	0	< 0.01
Midwest census region	0.38	0.18	0.03
South census region	0.13	0.67	< 0.01
West census region	0	0.15	0.01

Notes: The sample includes all 103 nuclear power reactors operating in the United States as of January 1, 2000. Column 3 reports p-values from tests that the means are equal in the two subsamples.
Source: 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

is to emphasize within-reactor changes in performance over time, which allows us to control for time-invariant observable and unobservable reactor characteristics. Then, in Section IIID, 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 that 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 nondivested reactors provide a reasonably accurate counterfactual for how operating performance would have evolved in divested reactors in the absence of deregulation.

III. Main Results

A. *The Effect of Divestiture on Nuclear Operating Performance*

Our empirical approach is described by the following regression equation:

$$Y_{it} = \beta_0 + \beta_1 1\,[Divested]_{it} + \beta_2 \mathbf{X}_{it} + \delta_i + \omega_t + \varepsilon_{it}. \tag{1}$$

Here, i indexes reactors and t indexes months, and we include all reactor-month observations from the period 1970–2009, amounting to over 36,000 total observations. In all specifications, the dependent variable Y_{it} is net generation as a percent of design capacity. The covariate of interest is $1[Divested]_{it}$, an indicator variable for reactors that have been sold and reclassified as nonutilities. The coefficient of interest β_1 is the effect of divestiture on operating performance in percentage points. In the full specification, we control for a cubic in reactor age $(\mathbf{X}_{it})$, reactor fixed effects (δ_i), and month-of-sample fixed effects (ω_t). Finally, the error term ε_{it} captures unobserved differences in performance across reactor-months.

Table 2 reports baseline estimates. Estimated coefficients and standard errors corresponding to $1[Divested]_{it}$ are reported from 5 separate regressions. Controlling only for month-of-sample fixed effects in column 1, divestiture is associated with a 6.3 percentage point increase in operating performance. As the mean of scaled net generation in our sample for nondivested plants in 2000 was 87 percent, the increase in divestiture is equivalent to an increase to approximately 93 percent. The coefficient is statistically significant with a *p*-value less than 0.001. Column 2 adds reactor fixed effects and the coefficient increases to 10.2. 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 IV, most of the variation in performance 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 electricity. In the United States, nuclear power is a \$48 billion annual market, accounting for 20 percent of total electricity production.[10] In 2010, independent power producers in the United States owned 46,798 megawatts of nuclear capacity, so a 10.0 percentage point increase implies 41 billion kilowatt hours of additional electricity production.[11] This is \$2.5 billion worth of power annually, almost enough power to meet electricity demand for all the households in New England.[12]

Moreover, this increase in operating performance is large enough to have substantial implications for the environment. Based on average emission levels from the US electricity sector, the increase in operating performance associated with

[10] In calculating the size of the market, we assumed an average wholesale price of \$60 per megawatt hour. US Department of Energy, Energy Information Administration, "Wholesale Market Data from Intercontinental Exchange" reports daily average wholesale prices for six major trading hubs (see www.eia.gov/electricity/wholesale). Over the period 2001–2009, the average wholesale price was \$61.00.

[11] US nuclear capacity by producer type is described in US Department of Energy, Energy Information Administration, *Electric Power Annual 2010*, revised December 2011, Table 1.1a "Existing New Summer Capacity by Energy Source and Producer Type." A 10.0 percentage point increase in net generation is (0.10)(46,798)(24 hours/day)(365 days/year)(1,000 kilowatts/megawatt) = 41 billion kilowatt hours.

[12] According to US 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.

Table 2—The Effect of Divestiture on Nuclear Operating Performance

	(1)	(2)	(3)	(4)	(5)
$1[Divested]_{it}$	6.3***	10.2***	10.0***	10.1***	9.5***
	(1.2)	(2.1)	(2.1)	(2.1)	(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
Observations	36,667	36,667	36,667	36,667	23,796
R^2	0.18	0.22	0.22	0.22	0.26

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.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

divestiture implies an annual decrease of 35 million metric tons of carbon dioxide emissions.[13] Using a conservative estimate for the social cost of carbon dioxide ($20 per ton), this implies an additional $700 million in benefits annually.[14] 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 US wind and solar generation combined over this period.[15] This reflects, in part, the fact that there was little US wind and solar generation until the end of the 2000s. However, it also makes the point that even modest improvements in operating performance can have substantial environmental implications when that technology makes up a large share of the total market.

[13] From US Department of Energy, Energy Information Administration, *Annual Energy Review 2010*, released October 2011, Table 11.6a, "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, 41 billion kilowatt hours of fossil fuel-based power implies (2.48)(41)(1,000,000)/(2.93) = 35 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.

[14] Federal Interagency Working Group (2010) presents a range of values for the social cost of carbon dioxide according to different discount rates and for different time periods that is intended to capture changes in net agricultural productivity, human health, property damages from increased flood risk, and other factors. With a 3 percent 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.

[15] According to US Department of Energy, Energy Information Administration, *Annual Energy Review 2010*, released October 2011, Table 8.2a, "Electricity Net Generation," during the period 2000–2009, US 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 10.0 percentage point increase in net generation is (0.10)(36,517)(24 hours/day)(365 days/year)(1,000 kilowatts/megawatt) = 32 billion kilowatt hours annually.

B. *Heterogeneous Effects*

Table 3 reports estimates from five separate regressions that describe the effect of divestiture by reactor type, reactor manufacturer, reactor vintage, type of sale, and for reactors in states with high and low average wholesale electricity prices. 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 13 cases and statistically significant at the 1 percent level in 12 out of 13 cases. In none of the five regressions can one reject the null hypothesis of equal coefficients. The uniformity of the results within and across columns indicates that the gains in operating performance were experienced broadly across different types of reactors.

The regression in column 4 tests whether gains differed depending on the type of sale. Of the 48 total divestitures, 19 (40 percent) 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 performance 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.

The coefficient estimates in column 5 indicate that the gains from divestiture were similar in states with high and low average wholesale prices.[16] This is a crude test because there could be other factors in addition to wholesale prices that vary across regions. This null result is consistent, however, with nonlinear costs of improving reliability. As emphasized earlier, the marginal cost of operating a nuclear plant is very low compared to wholesale prices so plant operators strive to keep reactors running as much as possible, regardless of the exact level of wholesale prices. Put another way, when prices are $50 per megawatt hour, plant operators are exerting considerable managerial effort toward improving reliability. At $70 per megawatt hour, the returns are somewhat higher, but they have already made all the changes that can be implemented easily, and additional improvements are either not possible or much more expensive.

Continuing to explore heterogeneity in the effect of divestiture, we now turn to variation across months of the year. Figure 2 plots point estimates and ninety-fifth percentile confidence intervals from a regression that allows the effect of divestiture to differ across calendar months. All 12 coefficient estimates are positive and statistically significant at the 5 percent 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 performance compared to, for example, the peak summer months when most reactors were running at close to full power even prior to the divestitures.

[16] For this exercise, we calculated average wholesale prices for 2001–2009 using data from US Department of Energy, Energy Information Administration, "Wholesale Market Data from Intercontinental Exchange." These data describe six major US electricity trading hubs, and we assigned each reactor to the closest wholesale market. Across hubs average prices range from $52 to $71 per megawatt hour (in year 2010 dollars), and we treat prices above the average price ($61) as "high."

Table 3—Heterogeneous Treatment Effects

	By reactor type (1)	By reactor manufacturer (2)	By reactor vintage (3)	By type of sale (4)	By average wholesale prices 2000–2009 (5)
Pressurized water reactors	9.4***				
($n = 22$)	(2.5)				
Boiling water reactors	10.6***				
($n = 26$)	(2.7)				
Westinghouse		9.9***			
($n = 20$)		(3.0)			
General Electric		10.6***			
($n = 22$)		(2.7)			
Combustion Engineering		5.7			
($n = 4$)		(3.4)			
Babcock and Wilcox		12.3***			
($n = 2$)		(1.9)			
Completed before 1975			10.1***		
($n = 17$)			(2.8)		
Completed 1975–1985			13.5***		
($n = 13$)			(3.6)		
Completed after 1985			7.1***		
($n = 18$)			(2.6)		
External sales				11.3***	
($n = 19$)				(2.8)	
Internal sales				9.2***	
($n = 29$)				(2.4)	
Reactors in states with high prices					9.4***
($n = 26$)					(2.5)
Reactors in states with low prices					11.0***
($n = 22$)					(2.7)
Month-of-sample fixed effects (480 months)	Yes	Yes	Yes	Yes	Yes
Reactor fixed effects (103 reactors)	Yes	Yes	Yes	Yes	Yes
Reactor age (cubic)	Yes	Yes	Yes	Yes	Yes
Observations	36,667	36,667	36,667	36,667	36,667
R^2	0.22	0.22	0.22	0.22	0.22

Notes: This table reports coefficient estimates and standard errors from five 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. In none of the five 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 0.69, 0.12, 0.32, 0.50, and 0.62, respectively.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

C. *The Effect of Consolidation on Nuclear Operating Performance*

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

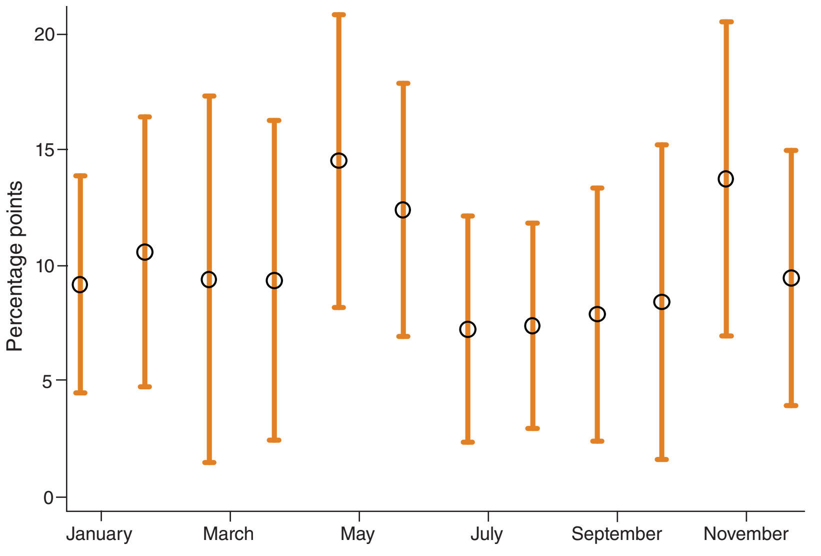

Figure 2. The Effect of Divestiture on Operating Performance by Month of Year

consolidated reactor operations among a smaller set of companies.[17] In this section, we examine empirically this interaction between deregulation and consolidation, comparing differences across reactors both in divestiture status and in the size of the company that operates each reactor. Determining the causal impact of company size is challenging because it reflects endogenous merger and acquisition decisions by plant operators. We use several different approaches to attempt to tease out causality, but these results should nonetheless be interpreted with caution.

Figure 3 plots the average number of reactors operated per company over the period 1970–2009. Averages are plotted separately by eventual divestiture status and are weighted by reactor not by company. As late as the mid-1990s, the average reactor was operated by a company that operated fewer than four reactors. Beginning in 2000 and 2001, there is a large increase in consolidation. By the end of the sample, the average divested reactor was operated by a company that operated between nine and ten reactors.

In principle, consolidation could improve operating performance 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 18 months, a consolidated nuclear company can hire highly skilled employees and train them to appreciate the idiosyncrasies of the company's reactor fleet.[18] Also,

[17] Economists have long recognized the potential gains in operating performance from consolidation in the nuclear power sector. 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."

[18] Robin Jeffrey, deputy chairman of British Energy, 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." See "Shut Down: Can Nuclear Plants Survive Deregulation? The Jury is Still Out," *Wall*

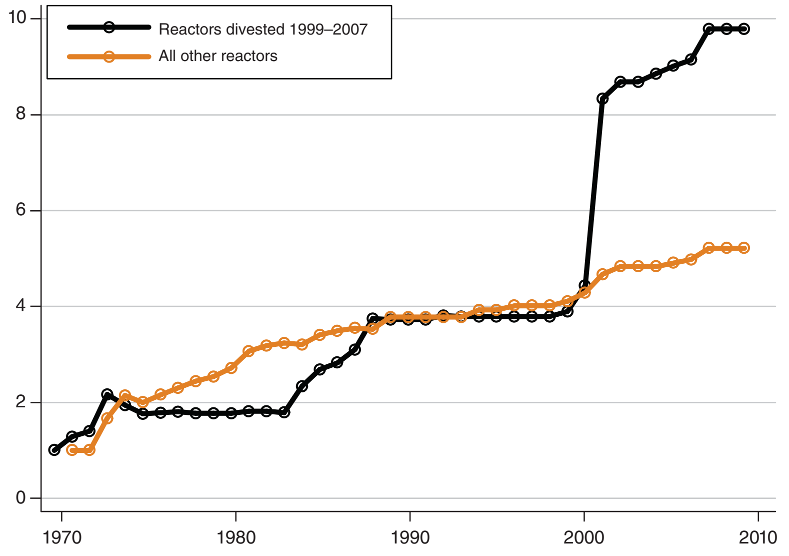

Figure 3: Average Number of Reactors per Company

within a consolidated company, employees can disseminate best practices for refueling and maintenance.[19] 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 operating performance.

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, Toledo Edison, Duquesne Lighting Company, and Centerior were combined to form First Energy in 1997. Second, there 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 0.47, implying that increasing by 1 the number of other reactors operated by the same operator improves performance by about 0.5 a percentage point.[20] Although the coefficient is not statistically significant, the point estimate is large enough to be economically important. The range of the consolidation variable is 1 to

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*.

[19] Anecdotal evidence suggests that this has indeed occurred. In "Executive Vows Strong Focus on Plant Safety" in *The Plain Dealer*, Cleveland, Ohio, March 9, 2004, 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." 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.

[20] 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.

Table 4—The Effect of Divestiture and Consolidation on Nuclear Operating Performance

	Reactor Level (1)	Reactor Level (2)	Reactor Level (3)	Reactor Level (4)	Reactor Level (5)	Plant Level (6)
$1[Divested]_{it}$	10.0*** (2.1)	7.7*** (2.4)	8.6*** (2.1)	8.6*** (2.1)	Excluding Divested Reactors	6.3*** (2.1)
Number of reactors/plants operated by the same reactor/plant operator	—	0.47 (0.30)	—	—	1.03** (0.42)	0.98** (0.41)
Number of same-type reactors (PWR/BWR) operated by the same reactor operator	—	—	0.53 (0.46)	—	—	—
Number of same-manufacturer reactors operated by the same reactor operator	—	—	—	0.58 (0.43)	—	—
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	—	4.4	3.1	2.7	3.9	2.5
Observations	36,667	36,667	36,667	36,667	19,446	23,796
R^2	0.22	0.22	0.22	0.22	0.21	0.27

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 for the period 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.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

17, so the point estimate implies that a change from the minimum to the maximum for this variable would increase performance by 8 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.[21] It is difficult to draw strong conclusions, however, because the parameter estimates are again imprecisely estimated.

[21] In related work, Lester and McCabe (1993) compares operating performance of US and French nuclear reactors. In contrast to the US experience, France early on adopted a single reactor design for all commercial reactors. Lester and McCabe (1993) argues that this standardization has increased learning-by-doing in plant operation and test empirically for differential learning among reactors of different designs.

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 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, 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.[22]

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 performance among nondivested reactors when reactors operated by the same company are divested. If there are spillovers within companies, then one might have expected an increase in performance 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 performance. In the regression, the estimated effect of divestiture on nondivested reactors is small and not statistically significant, providing no evidence for either hypothesis. However, there are only nine nondivested reactors operated by companies that operate at least one divested reactor, so these results are too imprecisely estimated to draw strong conclusions.

It is important to interpret all of these results with caution, because the pattern of consolidation reflects endogenous decisions by reactor operators. Much of the consolidation in the US 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 US reactors as of 2009).[23] The estimated coefficient

[22] An interesting question is whether these performance 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."

[23] Interestingly, prior to deregulation there is little evidence that these companies were the best managed. The three largest US nuclear companies as of 2009 are Exelon (formerly Commonwealth Edison), Entergy, and NextEra

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 suggestive evidence of performance 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 performance gains.

D. *Considering Possible Concerns about Selection Bias*

This subsection evaluates potential concerns about selection bias and differential trends in operating performance. From the mean characteristics reported in Table 1 it is clear that the divested reactors differ from the nondivested 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 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 number 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.[24] See column 2.

(formerly FPL Group). Between 1990 and 1998, reactors owned by these three companies had *lower* operating performance on average than other US reactors.

[24] 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 et al. (2001) identifies 16 states in which electric utilities were operating as of 2001 under some form of incentive regulation. Only ten of the states have nuclear reactors. When we reestimate the model using as a comparison group of only reactors operating in these 10 states, the estimate is 9.7 (3.3), consistent with the existing literature that finds little robust evidence that incentive regulation increases operating performance.

Table 5—Considering Possible Concerns about Selection Bias

	Excluding Michigan (1)	Excluding California (2)	Excluding Iowa and Wisconsin (3)	Divest date 1/2001 for all reactors (4)	Excluding the north-east census region (5)	Propensity score weighting (6)
$1[Divested]_{it}$	9.5***	10.3***	10.1***	7.7***	9.9***	10.9***
	(2.1)	(2.1)	(2.1)	(2.5)	(2.6)	(3.1)
Month-of-sample fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Reactor fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Reactor age (cubic)	Yes	Yes	Yes	Yes	Yes	Yes
Number of reactors	99	99	99	103	79	71
Observations	35,459	35,155	34,905	36,667	27,825	25,484
R^2	0.23	0.22	0.23	0.22	0.21	0.22

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. The sample includes monthly observations for the period 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. Standard errors are clustered at the plant level.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

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 including all of their nuclear reactors. 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 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 performance gains in nuclear reactors, or whether these decisions were driven by some other factor that is correlated with trends in operating performance. 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

Table 6—Considering Possible Concerns about Long Outages and Closures

	Excluding years 1996–1998 (1)	Excluding 12+ month outages 1996–1998 (2)	Excluding reactors with 12+ month outages 1996–1998 (3)	Including indicator variables for all 12+ month outages, during and after (4)	Including five closed reactors with imputed post-close operations (5)
$1[Divested]_{it}$	8.6***	9.0***	8.1***	7.2***	8.6***
	(2.1)	(1.9)	(2.0)	(1.5)	(1.7)
Month-of-sample fixed effects	Yes	Yes	Yes	Yes	Yes
Reactor fixed effects	Yes	Yes	Yes	Yes	Yes
Reactor age (cubic)	Yes	Yes	Yes	Yes	Yes
Number of reactors	103	103	93	103	108
Observations	32,963	36,452	33,177	36,667	38,705
R^2	0.24	0.22	0.23	0.34	0.22

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. The sample includes monthly observations for the period 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 4 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 5 includes observations from the five reactors in divesting states closed between 1993 and 1997 with imputed values after their close date.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

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 its operating performance. 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 nondivested 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 percent? 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.[25] Point

[25] 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

Table 7—Understanding the Mechanisms behind Post-Divestiture Gains

	(1)	(2)	(3)
A. Maximum generating capacity			
Maximum generation over last 12 operating months	2.4***	1.5	1.6
[Sample mean: 100.4]	(0.9)	(1.5)	(1.4)
Maximum licensed thermal capacity (MWt)	1.8	2.0*	1.9*
[Sample mean: 102.0]	(1.1)	(1.1)	(1.1)
B1. Operating days			
$1[Operating]_{it} \times 100$	3.9***	3.5*	3.8**
[Sample mean: 91.0]	(0.7)	(2.0)	(1.9)
B2. Length versus number of outages			
Number of outages per year	–0.17	–0.13	–0.13
[Sample mean: 1.7]	(0.11)	(0.16)	(0.16)
Mean outage length in days	–6.4***	–6.2	–6.9
[Sample mean: 19.1]	(1.3)	(5.4)	(5.3)
C. Capacity factor when operating			
Capacity factor in percent excluding zeros	–0.3	0.5	0.4
[Sample mean: 97.7]	(0.3)	(0.3)	(0.3)
Time effects (4,017 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 18 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 daily data from the NRC. Both measures of maximum generating capacity are expressed as a percent of the original design capacity.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

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 percent level provides additional evidence that the observed performance gains are not driven by selection.

The specifications described in the first four columns of Table 6 are aimed at assessing potential related concerns about long outages during the period 1996–1998 that cause the pronounced "dip" in performance 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 performance 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,

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.

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 5 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 to close plants at which they expected performance to degrade, while comparable plants in nondivesting 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 15 years before the closure to the 15 years after for the matched sample, and used those changes to impute post-closure output from the 5 reactors based on their 15-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 $1[Divested]_{it}$ declines only 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.

E. *Understanding the Mechanisms behind Post-Divestiture Gains*

We next turn to ancillary evidence aimed at understanding the mechanisms driving this observed increase in operating performance. Table 7 reports coefficient estimates corresponding to $1[Divested]_{it}$ for 6 alternative dependent variables. Regression coefficients are reported for three different specifications that 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. US 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 1,000 megawatt reactors. Controlling for reactor fixed effects and reactor age, divestiture is associated with an increase of 1.6–1.9 percentage points, although the coefficients are not statistically significant. Figure 4 performs an analogous graphical analysis, plotting mean licensed thermal capacity for divested and nondivested reactors as a percent of the original license. During the early 1970s, all reactors operated at their original licensed capacities. Capacity among divested reactors lags somewhat behind all other reactors during the 1990s but then increases sharply post-divestiture.[26] Viewed together with

[26] The experience in the 1990s is similar to the dip observed in operating performance among divested reactors for the period 1995–1998 and raises some of the same questions. One might be concerned, for example, that the

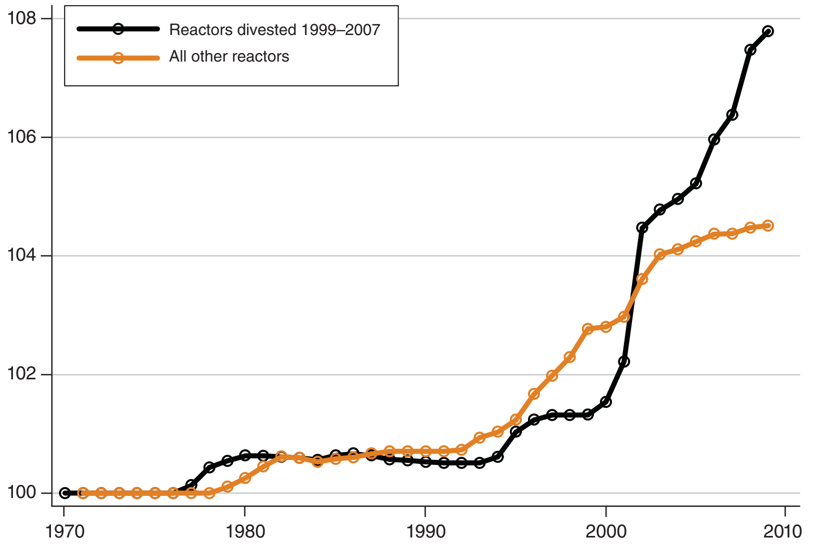

Figure 4: Licensed Thermal Capacity as a Percent of Original License

the regression estimates this provides suggestive evidence of a relationship between divestiture and increases in generating capacity.

Panel B1 of Table 7 focuses on reactor operating days. In the 1999–2009 period for which daily data are available, reactors are operating during 91 percent 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.[27] 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 nondivested 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.

We also tested whether divested reactors are systematically more likely to be operating when wholesale electricity prices are high. In particular, we estimated alternative specifications (not reported) with the divestiture indicator, the wholesale price, and the interaction between the two.[28] Including these additional covariates has essentially no impact on the estimated coefficient for divestiture, and the

difference in capacity during the 1990s could reflect owners of divested reactors differentially under-investing in capacity in anticipation of divestiture. This is plausible, although, in the early part of this period, deregulation efforts were just getting under way, so it is unlikely that plant owners forecast mandatory divestitures. Even if there was anticipation in the later years, this is unlikely to substantially bias our estimates. In particular, when we re-estimate the regression excluding 1994–1999, the results are almost exactly identical.

[27] In related work, Das et al. (2010) finds an increase in operating days at a steel plant in India in response to competitive pressures. Although the setting is very different, their analysis similarly finds improved operating performance along the "extensive" margin (i.e., the number of operating days) in addition to higher performance during operation.

[28] For this exercise we used daily weighted average wholesale prices from US Department of Energy, Energy Information Administration, "Wholesale Market Data from Intercontinental Exchange."

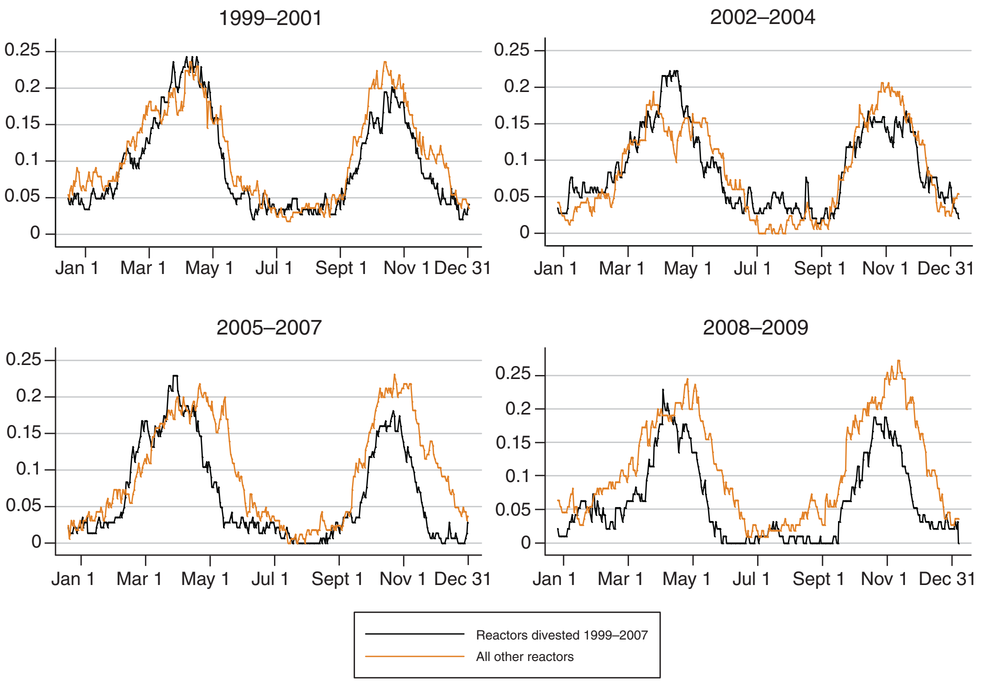

Figure 5. Fraction of Reactors Not Operating by Day of Year

estimated coefficients corresponding to wholesale price and the interaction term are close to zero and not statistically significant. From Figure 5 it is clear that both investor-owned utilities and independent power producers tend overwhelmingly to perform refueling and maintenance during the spring and fall, when wholesale prices are low. Given that outages are already being performed during these periods and that most outages are planned long in advance, there is little scope for increased efficiency along this margin.

Panel B2 of Table 7 pushes further on operating days, asking whether the increase in operating days is being driven by *fewer* outages or *shorter* outages. In the third column, divestiture is associated with an 8 percent decrease in the number of outages per year, and a 36 percent 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 of Table 7 examines capacity factor among operating reactors. The estimates are small in magnitude and not statistically significant. This is consistent with a graphical analysis (see Figure 6) that shows mean capacity factor by day of year is very similar for divested and nondivested 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.

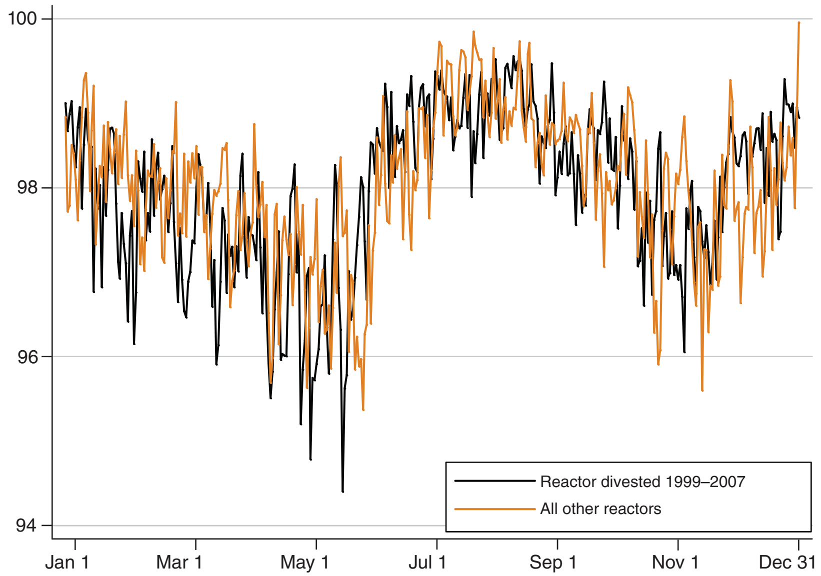

Figure 6. Mean Capacity Factor by Day of Year for Operating Reactors, 2005–2009

IV. Putting the Results in Context

This section places the results in broader context, attempting to evaluate to what extent the observed increase in operating performance represents an increase in economic *efficiency*. We find that divestiture and consolidation are associated with an increase in operating performance equivalent to 40 billion kilowatt hours annually, worth approximately $2.5 billion annually. These gains must be weighed, however, against several costs. This includes increased expenditure on production inputs including capital, fuel, and labor, as well as external costs from the increased use of nuclear power.

A. *Capital*

Perhaps the most striking feature of the observed increase in electricity generation was that it was achieved without building a single new plant or constructing a single mile of additional transmission capacity. The capital embodied in the plant itself and the associated transmission infrastructure is by far the most important input for nuclear power production, and the increase in operating performance should be seen as an increase in the productive efficiency of these assets. Construction costs represent about 70 percent of the total long-run cost of nuclear power, with the other 30 percent divided between incremental capital costs, fuel, and labor.[29] In this and the following two subsections, we examine the available evidence on these three inputs.

[29] 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

A large proportion of the capital investments made after the initial construction of a plant should best be viewed as fixed costs. For example, the Nuclear Regulatory Commission has overseen a steady improvement in electronic monitoring equipment over the life of these plants. This is equipment that is replaced intermittently as a function of equipment age regardless of the level of plant utilization. Even in cases where capital investments are clearly the result of "wear and tear," these reflect both time- and use-based depreciation.

Probably the most relevant capital expenditures for our purposes are those associated with increases in generating capacity. Section IIIE presented evidence that market restructuring is associated with approximately a 2 percent differential increase in maximum generating capacity, reflecting "uprates" of different sizes. Most are "measurement uncertainty recapture" uprates ($<$ 2 percent increase in generating capacity) and "stretch" uprates ($<$ 7 percent). These modest increases in capacity can typically be performed with little or no equipment replacement.[30] Larger, so-called "extended" uprates ($>$ 7 percent) typically require modifications to non-nuclear equipment, such as high-pressure turbines, condensate extraction pumps, motors, and transformers. The cost of these modifications varies widely, and we have seen estimates ranging from $100 to $1,000 per kilowatt of added capacity.[31] Extended uprates account for a bit less than half of the total increase in generating capacity. Thus, a 2 percent differential increase in capacity among divested reactors (~900 total MWe) could cost between $45 million and $450 million. Although not negligible, this is small compared to the value of the increased electrical generation. When comparing these dollar amounts to the $2.5 billion it is important to keep in mind that the equipment investments are a one-time investment that helps explain the increased *flow* of $2.5 billion annually.

B. *Fuel*

The input that is most clearly a *variable* cost is the enriched uranium fuel used for nuclear fission. Fuel utilization increases approximately proportionately with the level of electricity generation. MIT (2009) reports average fuel costs of $7 per MWh, including ore purchase, yellow cake conversion, and enrichment. Our results indicate that market restructuring is associated with an increase in generation of about 40 billion kilowatt hours annually. This implies a total increase in fuel expenditures of approximately $280 million annually.

We also examined aggregate data to see if there had been a change in fuel efficiency. Divestiture creates incentives for firms to increase output and decrease costs along all margins, including fuel efficiency. Plant-level fuel consumption is not

(72 percent). The other categories include incremental capital costs (7 percent), fuel and waste fees (10 percent), and labor and other nonfuel operations and maintenance costs (11 percent).

[30] Stretch uprates, for example, "usually involve changes to instrumentation setpoints but do not involve major plant modifications." See US Nuclear Regulatory Commission, "Types of Power Uprates," (see www.nrc.gov/reactors/operating/licensing/power-uprates/type-power.html). Accessed November 2011.

[31] See, for example, "Plant Allowed To Raise Output," *The News and Observer,* October 18, 2001 (~$150/kWe); "Notice by the NRC," *Federal Register,* November 16, 2001 (~$110/kWe); "New Plant from Old," *Nuclear Engineering International,* September 12, 2005 ($775–$1,000/kWe); "PPL Files Request to Increase Energy Production," *The Times-Tribune,* October 22, 2006 (~$1,050/kWe).

available, but between 1994 and 2009 total uranium fuel consumption and total nuclear electric generation increased at very similar rates, so we interpret this as providing no evidence of a change in efficiency along this margin.[32]

Increased electricity generation also means more spent nuclear fuel. Since 1983 the Department of Energy has collected a spent fuel waste fee of $1 per MWh from US nuclear reactors, intended eventually to finance a centralized storage facility for spent nuclear fuel. Currently, most spent fuel is stored onsite in storage pools or, increasingly, in dry cask storage. The total amount of spent fuel in storage at US nuclear plants increases at approximately 2,000 tons per year.[33] Fuel utilization is approximately proportional to total electricity generation, so the increase in operating performance associated with market restructuring implies approximately 100 tons in additional spent fuel annually. It is difficult to quantify the external costs of this additional spent fuel, but available estimates in the literature indicate that the private costs of on-site storage are relatively modest. A recent report commissioned by the US Department of Energy finds that total lifetime costs of dry cask storage including licensing, construction, loading, maintenance, and monitoring are about $110,000 per ton, implying, at a national level, $11 million in additional costs annually.[34]

C. *Labor*

Another important input in the production of nuclear power is labor. Market restructuring creates incentives for companies to increase the efficiency with which they use labor. At the same time, we have shown that divested plants tend to be operated more days of the year, which could require additional workers. Plant-level data is available to examine employment and salaries explicitly. These data come from EUCG, Inc., an association of electric-generating companies.[35]

Figures 7 and 8 plot the average number of workers and total labor expenditure per plant.[36] Employment tends to decrease over time for both divested and nondivested plants, with somewhat larger decreases among divested plants. This is consistent with existing evidence of modest labor reductions after divestiture at fossil-fuel-fired plants (Shanefelter 2008). Real average salaries (not shown) tend to increase disproportionately over this time period in divested plants, explaining why total

[32] According to US Department of Energy, Energy Information Administration, *Uranium Marketing Annual Report,* August 2010, the amount of uranium loaded into US nuclear power reactors increased 22 percent between 1994 and 2009 from 40.4 to 49.4 million pounds in 2009. During the same period, according to US Department of Energy, *Annual Energy Review 2010*, released October 2011, Table 9.2 "Nuclear Power Plant Operations" nuclear electricity net generation increased 25 percent from 640 to 799 billion kilowatt hours.

[33] US Nuclear Regulatory Commission 2011, "Information Digest, 2011–2012."

[34] See Idaho National Laboratory, *Advanced Fuel Cycle Cost Basis* INL/EXT-07–12107, Module E2 "Dry Storage of Spent Nuclear Fuel."

[35] An alternative source of data on both employment and capital expenditures is the Federal Energy Regulatory Commission's (FERC's) Form 1. Unfortunately, these data are collected from investor-owned utilities, but not from independent power producers, making it impossible to use FERC data for before and after comparisons.

[36] For confidentiality reasons, EUCG removed all identifying information from these data, so we are not able to estimate regressions of the form reported earlier in the paper. EUCG was willing, however, to code each plant as belonging either to the "Divested 1999–2007" or "All Other Reactors" groups, and these figures reflect this classification. By the end of the sample these data include all US nuclear plants, but, in 1997, included only three-fourths of all plants. Results are similar when we restrict the analysis to plants that reported employment data in at least 13 out of 14 years.

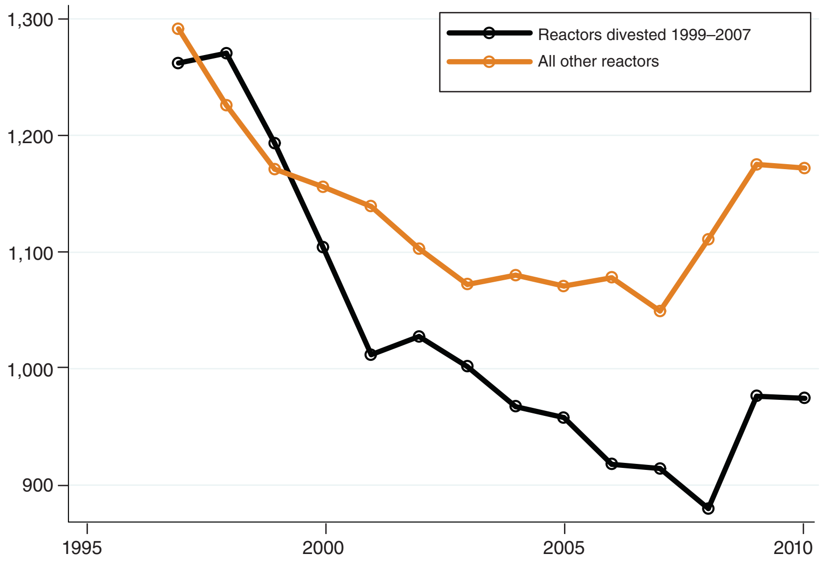

Figure 7. Average Number of Workers per Plant

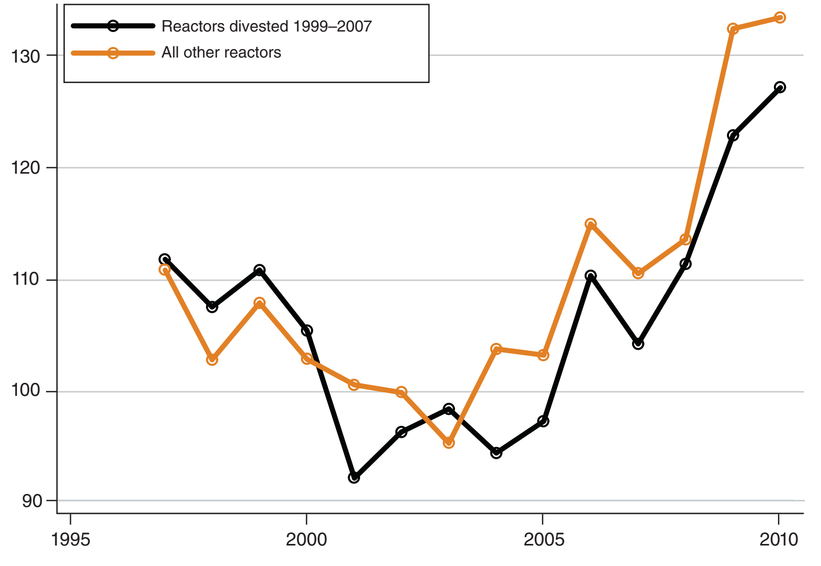

Figure 8. Total Labor Expenditure per Plant, in Millions

labor expenditure per plant tends to be very similar in divested and non-divested plants. Thus, the overall impact of market restructuring on labor expenditures seems to be close to zero.

It is now possible to add up the change in total expenditure on the three major inputs. Spending on fuel and associated storage costs have likely increased by approximately \$300 million annually. Capital expenditures have also likely increased but by an annualized cost of less than \$50 million. Labor expenditures appear to have remained essentially flat. These are the three main inputs to production. There may be other categories of expenditures that we have failed to account for, but they would have to be very large in magnitude to change this picture qualitatively. These costs must be weighed against approximately \$2.5 billion in increased annual revenue. Thus, it would appear that increased private costs offset less than 20 percent of the observed gains in operating performance.

D. *External Costs*

As we mentioned earlier, the change in operating performance has important implications for the environment, some of which are not currently internalized. Using a conservative estimate for the social cost of carbon dioxide, the implied carbon dioxide abatement implies \$700 million in benefits annually. Nuclear power generation does not produce carbon dioxide, and it also does not produce sulfur dioxide or other criteria pollutants. A recent study by Muller, Mendelsohn, and Nordhaus (2011) calculates that the external costs from sulfur dioxide, nitrogen oxides, and particulates from US coal-fired power generation exceed \$50 billion annually. To the extent that increased operating efficiency has decreased criteria pollutants this would represent additional social benefits. Accurately measuring the change in emissions of criteria pollutants is complicated, however, because in much of the country sulfur dioxide and nitrogen oxides are regulated under cap-and-trade programs, so decreases in emissions in some markets may be offset by increased emissions elsewhere.

Nuclear power brings with it, however, its own set of external costs. Probably most importantly, with nuclear power there are long-standing concerns about accidents. The Fukushima accident in March 2011 reminded the world that accidents can and do occur even with well-designed nuclear reactors. A Fukushima-type accident in the United States could cause damages easily amounting to tens of billions of dollars. A substantial engineering literature uses "probabilistic risk assessment" to identify potential catastrophic failures that would lead to reactor core damage. Estimated annual risks for US reactors tend to be very low, but there is a great deal of uncertainty about these estimates.

More difficult still is to quantify the *marginal* change in accident risk associated with the restructuring of electricity markets. Whereas economic theory provides clear predictions for operating performance, the effect of deregulation on safety is ambiguous and depends on whether safety is a complement or a substitute to operating performance (MIT 2003, Hausman 2011). In particular, some have argued that deregulation would lead to a decrease in safety as independent power producers cut corners in an attempt to increase short-term returns. Others have argued that safety and operating performance are complements, and that emphasizing safety is good business for companies who are heavily invested in nuclear because it decreases attention from regulators.

Table 8 reports estimates from three regressions aimed at evaluating the impact of divestiture on one measure of reactor safety. The estimating equation is the same as has been used in previous tables, except the dependent variable is an indicator variable for whether or not a reactor had an emergency shutdown, or "scram." These shutdowns are widely used as a measure of safety and feature prominently in NRC analyses. There is an average of 0.7 scrams per reactor year, or 0.2 percent of all reactor-days. In all three specifications, the point estimate corresponding to $1[Divested]_{it}$ is negative but only statistically significant at the 10 percent level. After adding reactor fixed effects in the second and third columns, the point estimates are large compared to the mean, implying a 30 percent decrease in scrams after divestiture. Coefficients are estimated with enough precision to reject increases larger than 5 percent.

In related work, Hausman (2011) finds similar results examining five additional measures of nuclear reactor safety. The paper finds no evidence of a decrease in safety associated with market restructuring. In some cases, safety appears to have actually improved. These results are consistent with the view that there are complementarities between safety and operating performance.[37] 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 the available measures of safety are far from perfect. What really matters from a safety perspective are catastrophic events. Fortunately, events like Three Mile Island, Chernobyl, and Fukushima are very infrequent, making them difficult to study empirically. There is certainly value in examining the available more high-frequency measures, but ultimately there are going to be limits to how much can be said about nuclear reactor safety using econometric analyses of historical data.

V. Conclusion

This paper examines an unprecedented period of deregulation and consolidation in the US nuclear power industry. We analyzed operating performance 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 percent increase in operating performance, with similar increases across reactors of different types, manufacturers, and vintages. This central result is robust across a variety of alternative sets of control variables and specification checks. In additional analyses aimed at understanding the mechanisms driving these results we show that the increase has occurred, most importantly, by decreasing the number of outage days per year.

These results provide some of the clearest evidence to date of the relationship between deregulation and efficiency in electricity markets. As predicted by economic theory, removing regulation has provided incentives for firms to increase operating performance, reduce costly outages, and make prudent investments in capacity. As plants have been sold to private companies, the financial cost of poor performance has

[37] Hubert Miller of the NRC makes the argument as follows, "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.

Table 8—The Effect of Divestiture on Emergency Shutdowns

	(1)	(2)	(3)
$1[Divested]_{it}$	–0.01	–0.06*	–0.06*
	(0.02)	(0.04)	(0.04)
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 three separate regressions. The dependent variable is an indicator variable for whether or not the reactor had an emergency shutdown, or "scram," in a given day. There is an average of 0.7 scrams per reactor year, or 0.2 percent of all reactor-days. For expositional purposes, we have multiplied the dependent variable by 100 so it has a mean of 0.2. The sample includes daily observations for 1999–2009 from all 103 nuclear power reactors operating in the United States as of January 1, 2000. Standard errors are clustered at the plant level.

transferred from ratepayers to shareholders, and companies like Exelon and Entergy have responded by achieving the highest levels of nuclear reactor operating performance in history.

Our paper also highlights an important relationship between nuclear operating performance 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 US 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. One of the broader lessons from our analysis is that even modest improvements in the operating performance 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 performance 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 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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