Deregulation and Investment in Generation Capacity: Evidence from Nuclear Power Uprates in the United States

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ABSTRACT

Nuclear power uprates are investments in generation capacity that enable reactors to operate beyond their original power limit. We find that owners of deregulated reactors are more likely to make investment in power uprates. Moreover, after deregulation owners of boiling water reactors are more likely to choose Extended Power Uprates (EPUs) that could add up to 20 percent of the original power, but owners of pressurized water reactors, another type of reactors for which EPUs are more technically challenging, tend to select other types of uprates that add less of reactor power. Deregulation incentivizes reactor owners to pursue profitable investments and propels them to make careful investment decisions more consistent with the technological nature of their plants.

Keywords: Deregulation, Power uprate, Investment, Efficiency, Generation capacity, Nuclear energy, Electricity market

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I. INTRODUCTION

Economic theories have long argued that market deregulation and competition change firm investment incentives, leading to potentially significant gains in social welfare. Under traditional rate of return regulation, firms have strong incentives to engage in excessive capital investment if the allowed return rate exceeds the cost of capital (Averch and Johnson, 1962), as evidenced by over-buildup of nuclear power plants in the U.S. in late 1960s and 1970s; meanwhile regulated firms have less motivation to invest in efficiency and technological innovation. With economic deregulation, firms are not only discouraged from excessively investing in capital, but also incentivized to pursue profitable investment opportunities because they are no longer limited to a "capped" rate of return (Joskow and Rose, 1989; Borenstein and Bushnell, 2000).

This paper provides the first comprehensive study on the impacts of deregulation on investment in power uprates by owners of U.S. nuclear power reactors. Nuclear power uprates allow a nuclear reactor to operate beyond its originally licensed thermal power limit,[1] thus increasing its

1. Advances in nuclear engineering and better understanding of the performance of the existing nuclear fleet have enabled nuclear power uprates.

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electricity generation capacity (IAEA 2004).[2] Since nuclear reactors have a significant fuel cost advantage over coal and gas fired plants, power uprates allow plant owners to gain the most from their nuclear units. Indeed, the U.S. nuclear industry has, through power uprates, added over 20,000 megawatts-thermal (MWt) of reactor power to the existing fleet, equivalent to six new full size reactors.[3] Over 70 percent of this increase was due to power uprates that were applied for after year 2000 when electricity restructuring took place in many states.

We study power uprate applications submitted by investor-owned reactors to the U.S. Nuclear Regulatory Commission (NRC) between 1991 and 2012. We employ a Difference-in-Differences (DID) strategy and investigate the change in power uprates by eventually-deregulated reactors after versus before deregulation, using always-regulated reactors as the control group. First, we find that deregulation incentivized reactor owners to invest in power uprates. On average the owner of a deregulated reactor is more than twice as likely to invest in power uprates than that of a regulated reactor. Second, we find that even for such generally profitable power uprate investments, owners of deregulated reactors make careful decisions that are consistent with the technological characteristics of their plants. After deregulation, the two types of nuclear reactors, Boiling Water Reactors (BWRs) versus Pressurized Water Reactors (PWRs), differ in which types of power uprates to pursue. Owners of deregulated BWRs are more likely to choose Extended Power Uprates (EPUs) that could increase the reactor thermal power by up to 20 percent. In contrast, owners of deregulated PWRs, for which EPUs are more technically challenging, risky and expensive due to imbedded technical constraints, tend to choose Stretch Power Uprates (SPUs) or Measurement Uncertain Recaptures (MURs) that typically add two to seven percent of the original thermal power.

Our study suggests that deregulation and competition provide incentives above those of regulated markets for firms to invest in generation capacity if such investments are profitable and the rate of return is higher than the allowed return under regulation. Deregulation allows firms to capture uncapped profit. At the same time, with no guaranteed “normal” returns on investments, firms under deregulation and competition are propelled to make careful investment decisions, as shown by their choices on types of power uprates for deregulated BWRs versus PWRs.

Our work provides a unique perspective on the impacts of deregulation in electricity markets on firm incentives and efficiency in capital investment. The literature has so far focused on the effects of increased uncertainty in restructured markets on investment, showing that power generators in restructured markets delay or are less likely in investing in new generation capacity and capital intensive pollution abatement equipment (Fowlie, 2010; Ishii and Yan, 2011; Fabrizio, 2012). Our study focuses on investment in nuclear generating capacity for which profitability uncertainty is of less concern because of the baseload nature of nuclear power. This allows us to identify incentives for investment by owners of deregulated reactors, shielding the impacts of uncertainty on such decisions.

Our paper also proposes a novel indicator for deregulation. We determine the regulatory status of a nuclear reactor base on whether it is removed from the regulatory rate-base of the utility owning it (according to the financial statements of the utility). We consider our proposed deregu-

2. A reactor thermal power level (often in megawatts-thermal, *MWt*) refers to the total reactor core heat transfer rate to the reactor coolant, e.g. light water. During heat transfer, steam is formed and directed to the main turbine generator to produce electricity. Thus a reactor thermal power level is different from its generation capacity (in megawatts-electricity, *MWe*), the maximum amount of electricity a generator can produce. Approximately 3 megawatts-thermal (MWt) equal to 1 megawatt-electricity (MWe).

3. See U.S. NRC, “Status of Power Uprate Applications.” Retrieved October 21, 2013, http://www.nrc.gov/reactors/operating/licensing/power-uprates/status-power-apps.html

lation indicator to be more accurate in determining whether a plant is deregulated than currently used indicators that are either based on the state level enactment of electricity restructuring or on the divesture of the plant. As such, our proposed indicator could be useful in future studies on electricity restructuring.

This paper contributes to a large literature, both theoretical and empirical, on the effects of economic regulation (and deregulation) and competition on firm investments in capital and in research and development (Cohen and Levin, 1989; Joskow and Rose, 1989; Aghion et al., 2001; Alesina et al., 2005). It is also related to a strand of literature that has shown significantly positive impacts of deregulation or divesture on operating efficiency and safety of nuclear plants (Zhang, 2007; Davis and Wolfram, 2012; Hausman, 2014).[4] In particular, Davis and Wolfram (2012), a very interesting study focusing on nuclear reactor divesture and operating efficiency, includes a brief discussion on the impacts of divesture on overall power uprates as one of the channels for improvement in nuclear operating efficiency after divesture. In this paper, we consider nuclear power uprates as relating to the broader economic issue of firm incentives for investment, and study in detail the effects of deregulation on investment in power uprates (both overall and by different types) by owners of BWRs and PWRs, respectively.

The remainder of the paper is organized as follows. Section II provides background on nuclear power uprates. Section III discusses our hypotheses regarding deregulation and investment in power uprates. Section IV presents data. We then discuss empirical results on the effects of deregulation on nuclear power uprates overall in Section V, and results on the choices of uprate types for deregulated BWRs and PWRs in Section VI, respectively. Section VII concludes the paper.

II. BACKGROUND

II.1 Commercial Power Reactors in the U.S.

There were 35 Boiling Water Reactors (BWRs) and 69 Pressurized Water Reactors (PWRs), for a total of 104 light-water commercial power reactors in the U.S. at the end of 2012, all utilizing normal water as coolant and neutron moderator.[5] In BWRs, demineralized water (reactor coolant) moves upward through the reactor core and absorbs heat generated from fission reaction in nuclear fuel, producing a steam water mixture inside the reactor vessel. After removal of water through a moisture separator, the steam is then directed to turn the main turbine and the attached electrical generator.[6] All the BWRs currently in service in the U.S. are designed by General Electric (GE).

In contrast, PWRs employ two major systems to convert energy generated by nuclear fission into electric power. In the first system, a reactor coolant system, transfers heat (carried by water under pressure) from nuclear fuel to a steam generator, while the second system transfers steam formed in the steam generator to the main turbine generator to produce electricity.[7] Reactor

4. There exist a number of studies focused on restructuring and electricity production from fossil-fuel plants (see Wolfram, 2004; Bushnell and Wolfram, 2005; Fabrizio, Rose, and Wolfram, 2007, and Craig and Savage, 2013).

5. There are also heavy-water reactors, which, unlike light-water reactors, use deuterium oxide (D_2O) as coolant and moderator. They are largely deployed in Canada.

6. See U.S. NRC Reactor Concepts Manual – Boiling Water Reactor Systems. Retrieved August 13, 2012 from http://www.nrc.gov/reading-rm/basic-ref/teachers/03.pdf

7. See U.S. NRC Reactor Concepts Manual – Pressurized Water Reactor Systems. Retrieved August 13, 2012 from http://www.nrc.gov/reading-rm/basic-ref/teachers/04.pdf

coolant systems in commercial PWRs in the U.S. are designed by three vendors (Westinghouse, Combustion Engineering, and Babcock & Wilcox) and consist of similar major components that are arranged in different ways.[8]

These nuclear reactors are baseload generators and produce about 20 percent of electricity in the U.S.[9] Compared to coal and natural gas plants, nuclear reactors produce electricity at a lower marginal cost,[10] and have a potential commercial advantage in that they do not emit carbon dioxide.

Building new nuclear reactors, however, is very expensive (in several billions of dollars). The estimated levelized capital cost for advanced new nuclear plants is about $83.4 per MWh (megawatt-hour), higher than that of conventional coal plants or combined cycle natural gas plants (about $65.7 and $15.8 per MWh, respectively).[11] Thus building new nuclear reactors often involves financial assistance from the government including loan guarantee and production tax credits, as well as limited financial liability from potential nuclear accidents.

II.2 Nuclear Power Uprates in the U.S.

A nuclear power uprate increases a reactor's maximum thermal power limit, by digitalizing instrumentation and control systems, utilizing initial design margins that have become too conservative with current technologies and better understanding of reactor operation, and refurbishing turbine generators and other balance-of-plant (BOP) equipment (IAEA, 2004). As the nuclear plant site is already licensed, the reactor owners only need to submit an in-depth analysis on potential safety impacts of the power uprate, when making a request to the NRC for amending the maximum reactor core thermal power level.

U.S. nuclear power plants have been performing power uprates since late 1970s. However, it is only since the late 1990s that power uprates have become common. As shown in Figure 1, over 17,000 MWt of power uprates were applied during the period of 2000–2012, compared to only around 5,000 MWt in total during the prior-to-2000 period.

Nuclear power uprates are categorized by the NRC into three types: Measurement Uncertainty Recaptures (MURs), Stretch Power Uprates (SPUs), and Extended Power Uprates (EPUs). MURs involve a less than two percent increase in power output, achieved by replacing traditional flow meters with ultrasonic measurement devices to more precisely measure feedwater flow. SPUs can achieve up to a seven percent increase in the thermal power level, usually taking advantage of design margins (which were originally built into the reactors but have become too conservative) and involving only moderate equipment replacement (Thomas, 2009; U.S. NRC, 1992). EPUs can lead to up to a 20 percent increase in the thermal power level, and require significant modifications to major equipment. It is both costly (often in hundreds of million dollars) and challenging for a reactor to perform an EPU. Moreover, EPUs, even with major plant modifications, are not risk free.[12]

8. PWRs was originally designed for U.S. nuclear submarines in early 1950s.

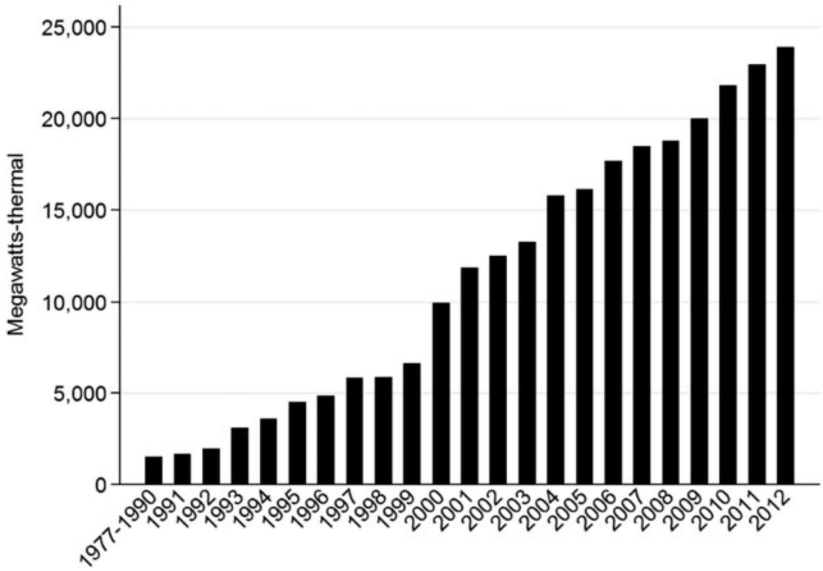
9. See U.S. Department of Energy, Energy Information Administration, *Annual Energy Review*, Released September 27, 2012, Table 7.2a, "Electricity Net Generation: Total (All Sectors), 1949–2011."

10. MIT (2009) reports fuel costs (per megawatt hour) of $23 and $48 for coal-and natural gas-fired power plants, but only $7 for nuclear power.

11. See U.S. Energy Information Administration (2013, January) "Levelized Cost of New Generation Resources in the Annual Energy Outlook 2013". Retrieved July 17, 2013, from http://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf

12. See Appendix A for a more detailed discussion on the three types of nuclear uprates.

Figure 1: Cumulative addition of thermal power in the U.S. due to power uprates, 1977–2012 (in MWt)



Data source: U.S. NRC Status of Power Uprate Applications

Technical feasibility of power uprates for BWRs and PWRs

MURs and SPUs have been widely performed by both PWRs and BWRs. However, fewer EPUs have been undertaken by PWRs than by BWRs, for several reasons. First, the capacity of steam generators in PWRs is a major constraint in realizing the potential of EPUs (IAEA, 2011). In some cases the degradation of a steam generator could substantially decrease its functionality, requiring very costly replacement of the entire steam generators to enable EPUs.[13] Second, replacement of steam generators could be risky by creating potential unforeseeable risks that could be devastating to PWR plants. For example, when the San Onofre nuclear plant replaced the old steam generators in 2010–2011 for its two Combustion Engineering PWR units in preparation for future EPUs, faults were discovered in new steam generators and the plant was shut down and then retired prematurely.[14] In contrast, BWRs have no steam generators and thus no such technical constraints and risks when performing EPUs. Finally, the ability to perform EPUs is related to the nature of margins (both design and analytical) originally built into the plant (Schimmoller, 2000). Relative to BWRs, PWRs have less margins to accommodate the significant increase in steam flow rates associated with EPUs (Hansen, 2007).[15]

13. A complete replacement of steam generators at a three loop PWR in the U.S. costs between $125–153 million (Wade, 1995).

14. The San Onofre plant was initially shut down in January 2012. In June 2013, Southern California Edison, the owner of the plant, decided to retire both reactors prematurely, due to the uncertainty surrounding regulatory approval of restarting the reactors and costs of repairing the steam generators. See World Nuclear News (2013, June 7). "Regulatory delay closes San Onofre."

15. For example, most BWRs perform loss-of-coolant accident (LOCA) and emergency core cooling system (ECCS) analyses at 105 percent of full power, whereas most PWRs perform at 102 percent of full power.

Appeal of nuclear power uprates

Relative to new nuclear builds, nuclear power uprates provide a low-cost way to increase generation capacity, while maintaining the lower marginal generation cost than coal and natural gas fired plants.[16] The payback period of power uprates tends to be rapid (Kim, 2005). For example, Entergy Corporation spent approximately $300 million in power uprates to obtain an additional power of over 1380 MWt (equivalent to 460 MWe) in its nuclear plants in New York and New England between 2003 and 2006,[17] at an average capital cost of $650 per kWe (Young and Abney, 2003). Assuming a wholesale electricity price of $55 per MWh and a capacity factor of 92%,[18] this 460 MWe additional generation capacity amounts to additional revenue of $204 million per year.[19] This, in turn, implies a payback period of only eighteen months.[20]

Upfront costs of power uprates vary among the three types of uprates, depending on plant design features and uprate parameters. It usually takes less than $10 million to perform a MUR, but over $100 million to undertake a 20 percent EPU (Fabian, 2005). On the basis of cost per kilowatt generation capacity (kWe), not only are power uprates much less costly than new nuclear builds, but also less expensive than fossil fuel fired plants.[21]

III. CONCEPTUAL FRAMEWORK

III.1 Electricity Market Restructuring and Investment in Generation Capacity

Historically U.S. electricity markets were regulated by state Public Utilities Commissions (PUCs). Vertically integrated and regulated electric utilities received exclusive rights to provide electricity within given geographic areas, and charged rates set by the cost of service regulation that allows them to recover recurring operating expenses and earn a "normal" rate of return on capital investment.

The Energy Policy Act of 1992 and Federal Energy Regulatory Commission (FERC) Order 888 in 1996 opened transmission access to non-utility generators. In the late 1990s several states restructured their electricity markets, separating electricity generation (which most economists believe is naturally competitive) from transmission and distribution (which is generally believed not

16. As Andy White, president and CEO of GE Energy's nuclear operations, explained, "When you look at the economics of existing nuclear units versus coal and gas units, it is easy to see why every megawatt from nuclear power is valuable. . .. For that reason, owners are trying to get the most from their nuclear units [through power uprates]". See Hansen (2007).

17. These plants include Indian Point Unit 2 and 3 in New York, Pilgrim Unit 1 in Massachusetts, and Vermont Yankee in Vermont.

18. A wholesale electricity price of $55 per MWh is based on the average wholesale day-ahead peak price at NYISO A Hub ($49 per MWh) and at NEPOOL Mass Hub ($61 per MWh) between 2007 and 2012. A capacity factor of 92% is the average capacity factor for Entergy's merchant nuclear fleet between 2007 and 2012.

19. The net present value of this power uprate investment also depends on how long the reactor will operate (i.e., its license extension status and license expiration date).

20. Power uprates also involve significant plant design re-analysis and plant hardware upgrading, likely improving plant operational safety (IAEA, 2004).

21. The estimated overnight cost is (in 2005 dollars) in the range of $400 to $800 per kWe capacity for SPUs (Kim, 2005; Fabian, 2005; Kang, 2008), and less than $2,000 per kWe for EPUs. Per-kilowatt cost estimate for MURs is expected to be much less than that of SPUs or EPUs. In comparison, the estimated overnight cost of a new nuclear build is as high as over $6,000 per kWe. The upfront cost of coal plants ranges from $1,280 to $1,360 per kWe without carbon capture, and from $2,090 to $ 2,270 with carbon capture (MIT, 2007). For natural gas combined-cycle (NGCC) plants with carbon capture and storage, the estimated construction costs are somewhere between $892 and $1,781 per kWe (MIT, 2011).

to be competitive). Wholesale electricity markets were established in several regions and entry by independent power producers was allowed. Utilities were also mandated or encouraged to divest all or part of their generating portfolios.[22]

Economists have argued that as long as the regulated rate of return exceeds the cost of capital, regulated utilities have incentives to make excessive capital-intensive investment, particularly in generation capacity, since their profit is based on capital expenditure (Averch and Johnson, 1962). Regulated utilities are also less motivated to make investments to improve operation efficiency and technology, as their profit rates are capped (Atkinson and Halvorson, 1980; Granderson and Linvill, 2002).

With deregulation, firms face no ceiling on their investment returns and thus have stronger incentives to pursue profitable investments that yield returns higher than regulated rates (Borenstein and Bushnell, 2000). Meanwhile, deregulated firms, when expanding their productive capacity, do not have as many regulatory burdens as regulated ones, since regulated utilities have to get approval from both the NRC and state PUCs. Moreover, competition (likely leading to lower and more volatile electricity prices) could motivate firms to be more careful and make more efficient investment decisions.[23]

III.2 Electricity Deregulation and Nuclear Power Uprates: Hypotheses

With deregulation, power uprates, though no longer guaranteed return, provide a highly cost-effective way to add generation capacity to existing nuclear plants. They are generally very profitable, since incumbent nuclear reactors possess competitive advantages in marginal production costs and are infra-marginal suppliers in competitive wholesale market. Moreover, potential risks associated with power uprates are generally small and manageable (except for EPUs on PWRs). Therefore power uprates could be very attractive to owners of deregulated nuclear reactors who now are able to appropriate whatever profit they can make and thus incentivized to seek projects of as high profitability as possible.

Moreover, if some market power is present in competitive wholesale electricity markets,[24] a company with a portfolio of nuclear and non-nuclear generating plants may have incentives to invest in nuclear power uprates to increase its infra-marginal capacity. This allows them to exercise market power by withholding output from its marginal plants.

Thus, our Hypothesis I (regarding overall power uprates): *Owners of deregulated nuclear reactors are more likely to apply for power uprates, relative to those of regulated reactors.*

In terms of owners' choices of different types of nuclear uprates, we conjecture that for deregulated BWRs, EPUs would be the most profitable option because: (1) they provide an economic way to maximize added power level (up to a 20 percent increase) and thus revenue and profit, and (2) the upfront cost of EPUs (around $100–300 million), though much higher than that of MURs and SPUs, is manageable for owners of nuclear generators.

22. See White et al. (1996) and Joskow (1997) for overviews of the electricity restructuring process.

23. On the other hand, there have been arguments that deregulated wholesale markets do not provide appropriate incentives for investment in peaking capacity (Joskow, 2006; Crampton and Ockenfels, 2011). Joskow (2006), however, suggests that any problem of inadequate investment in peaking capacity in deregulated markets is mainly due to a number of market imperfections and institutional constraints, not deregulation itself. Since nuclear generation is baseload, this issue is not directly related to our study here.

24. Market power in deregulated electricity markets has been a concern (see, e.g., Wolfram, 1999; Borenstein and Bushnell, 2000; and Joskow and Kahn, 2002).

However, given that PWRs have inherent technical limitations in performing EPUs (particularly those associated with functionality and replacement of steam generators) and potential risk and significant financial cost, owners of deregulated PWRs may be more likely to choose SPUs and MURs, rather than EPUs.[25] It is also noteworthy that although MURs only entail an additional two percent of thermal power, they are easy to implement and much less expensive. Thus MURs could be as attractive as SPUs for deregulated PWRs.

Therefore our Hypothesis II (regarding choices of power uprates): *Owners of deregulated BWR reactors are more likely to perform EPUs, whereas owners of deregulated PWR reactors are more likely to undertake SPUs and MURs, relative to regulated reactors.*

IV. DATA

IV.1 Data Description[26]

The data involves power uprate applications submitted to the NRC between 1991 and 2012, by nuclear reactors owned by investor-owned-utilities (IOUs) or independent power producers (IPPs).[27] Table 1 focuses on the 88 investor-owned nuclear reactors in the U.S., whose owners did not apply for the same type of power uprate more than once.[28] We distinguish them according to types and sequences of uprate applications. For the 12 reactors that have had SPUs (which was the only type of uprate available then) before 1991, nine had only one power uprate later during 1991–2012, and no reactor had another SPU application. For the 76 reactors whose owners did not apply for SPUs before 1991, almost half had only one uprate during 1991–2012. The other half had multiple and different power uprates, with a large majority involving MUR and SPU or MUR and EPU combinations and a small minority involving SPU and EPU or all the three types of power uprates. For reactors whose owners have applied for multiple uprates including a MUR, some applied for the MUR first and others applied the MUR after other types of uprates, suggesting that performing a MUR does not affect the reactor's opportunities for undertaking a SPU or an EPU, and *vice versa*. In contrast, of the reactors that have had both a SPU and an EPU, none undertook an EPU first, indicating that an EPU might exhaust a reactor's design margins and render a further SPU unlikely. These statistics suggests that that the types and the sequence of power uprates that a reactor has previously performed affect its current choices for power uprates.

25. For example, Indian Point Unit 3 (a Westinghouse 4-Loop PWR) developed five scenarios of possible thermal power increase, with the overall cost estimates ranging from $35 million ($700 per KWe) for a SPU of 148.6 MWt, to $235 million ($1,500 per KWe) for an EPU of 469.6 MWt. The owner, Entergy, eventually decided to proceed with a SPU in 2004, instead of an EPU (Kang, 2008).

26. See Appendix B for a detailed description on the analytic data and data sources.

27. All the power uprate applications in the data have been approved by the NRC without significant modification to requested amount of uprates, except for two rare cases where the owners of the plants, which are always-regulated, decided to withdraw or put on hold of thier applications (see Appendix B). There is some lag between filing applications by nuclear reactor owners and NRC approval.

28. Of the 104 reactors in the U.S., eight are exclusively or majorly owned by federal, state, municipal agencies, or electric cooperatives; and five reactors are owned by a diverse mix of an investor-owned utility, electric cooperatives, and municipality groups with the ownership of investor-owned utilities less than 50 percent. Of the remaining 91 investor-owned reactors, three have undertaken the same type of power uprate more than once, a rarity possibly due to plant-specific circumstances suggesting that once a reactor undertakes a certain type of power uprate, it may have exhausted the option of performing the same type of uprate again. Thus the three reactors that performed the same type of uprate more than once are likely to be outliers, which we exclude them in the analyses. The econometric results still hold if they are included.

Table 1: Distribution of Reactors, by Types and Sequences of Power Uprates They Applied Between 1991 and 2012

Type and Sequence of Power Uprates	The 12 reactors with SPUs before 1991	The 76 reactors without SPUs before 1991
	# of reactors that have applied no power uprate between 1991 and 2012	
No uprates	3	4
	# of reactors that have applied one power uprate between 1991 and 2012	
MUR	6	16
SPU	0	10
EPU	3	8
	# of reactors that have applied two power uprates between 1991 and 2012	
MUR-SPU	0	5
MUR-EPU	0	7
SPU-MUR	0	15
SPU-EPU	0	5
EPU-MUR	0	0
EPU-SPU	0	0
	# of reactors that have applied three power uprates between 1991 and 2012	
MUR-SPU-EPU	0	0
MUR-EPU-SPU	0	0
SPU-MUR-EPU	0	4
SPU-EPU-MUR	0	2
EPU-MUR-SPU	0	0
EPU-SPU-MUR	0	0

Note: We focus on the 88 investor-owned nuclear reactors in the U.S. whose owners did not apply for the same type of power uprate more than once.

Table 2 distinguishes uprate applications by reactor types in two dimensions (BWRs versus PWRs; and eventually-deregulated versus always-regulated) and by two time periods (1991 to 1998 versus 1999 to 2012, roughly before- versus after- deregulation). Panel A of Table 2 focuses on the 76 reactors whose owners did not apply for SPUs before 1991. More than half of BWRs (17 out of 29) had EPUs during 1991–2012, as opposed to only 20 percent (nine out of 47) had PWRs. This is consistent with the idea that EPUs are more technically challenging and risky and expensive for PWRs, due to their steam generators and built-in design margins. On the other hand, 29 BWRs have applied for 14 MURs and 18 SPUs, and 47 PWRs for 35 MURs and 22 SPUs, suggesting that MURs and SPUs are both feasible for the two types of reactors.

Moreover, the data suggests that after deregulation owners of BWRs accelerated their applications for EPUs, while owners of PWRs more actively undertook SPUs. Owners of eventually-deregulated BWRs submitted no EPU applications before 1999 but 12 EPU applications afterwards, whereas owners of always-regulated BWRs had two and three EPU applications before and after 1999 respectively. For eventually-deregulated PWRs, however, their owners applied for two SPUs before 1999 but 10 afterwards, while owners of always-regulated PWRs submitted eight and two SPU applications before and after 1999, respectively.[29]

29. In Panel B of Table 2, we include the 12 reactors that had SPUs prior to 1991 and find similar patterns regarding the choice of power uprates by deregulated BWRs and PWRs, respectively.

Table 2: Power Uprates Applied Between 1991 and 2012, by Reactor Type and Reactor Regulatory Status

	1991-1998			1999-2012		
	# of MURs	# of SPUs	# of EPUs	# of MURs	# of SPUs	# of EPUs
Panel A: 76 reactors (excluding 12 reactors that had SPUs before 1991)						
7 BWRs [Always-regulated]	0	5	2	4	1	3
22 BWRs [Eventually-deregulated]	0	9	0	10	3	12
25 PWRs [Always-regulated]	0	8	0	15	2	4
22 PWRs [Eventually-deregulated]	0	2	0	20	10	5
Panel B: 88 reactors (including 12 reactors that had SPUs before 1991)						
7 BWRs [Always-regulated]	0	5	2	4	1	3
23 BWRs [Eventually-deregulated]	0	9	0	10	3	13
29 PWRs [Always-regulated]	0	8	0	16	2	6
29 PWRs [Eventually-deregulated]	0	2	0	25	10	5

Note: The data includes all power uprate applications submitted to NRC between 1991 and 2012 by the reactors in the sample.

IV.2 Indicator for Nuclear Reactor Deregulation

To test the impacts of deregulation on nuclear reactor owners' investment in power uprates, we construct a time varying binary indicator, *PUC_DEREG*, which takes the value of one if a reactor is removed from a regulatory rate-base and its investments (including power uprate projects) are no longer subject to guaranteed rate-of-return regulation by the state PUC, and zero otherwise. We characterize a reactor to become "removed from the regulatory rate-base" when the electric utility owning it discontinues the application of Statement of Financial Accounting Standards (SFAS) No. 71 to its nuclear generation assets,[30] or divests it to independent power producers.[31,32]

30. Under traditional rate-of-return regulation where "prudently" incurred costs are recovered from customers with a normal rate-of-return on capital investment, regulators may require electric utilities to defer collecting from customers some of its costs until a future date. These deferred costs are recorded as regulatory assets in financial statements pursuant to the criteria of SFAS No. 71. When an electric utility is deregulated it should no longer apply SFAS No. 71 to the generation portion of its business. The utility instead reports in its SEC annual 10-K filing the impairment of its regulatory assets (e.g. the loss associated with its generation assets no longer recoverable from future cash inflows previously determined by state regulator in the rate-making process). The utility then becomes the residual claimant of profits accrued to its generation business.

31. Several states suspended restructuring or re-regulated the market following the California crisis in 2000. Among them, only Virginia has nuclear reactors in our sample (reactors in Arizona have a diverse of ownership and are not included in the study). After the re-regulation, the four Virginia reactors were put back by the utilities into their regulatory rate-base in April 2007. We carefully changed their *PUC_DEREG* indicator back to zero after year 2008 in all regressions.

32. We examined SEC filings of nuclear plants to identify those deregulation activities. See Appendix E for the complete list of deregulation and divesture activities on nuclear reactors in the U.S.

Our *PUC_DEREG* indicator differs from two alternative indicators of market restructuring used in other studies. In her study on the impacts of electricity restructuring on nuclear plants' capacity factors, Zhang (2007) used an indicator of *STATE_RESTRUCTURE*, whose value changes from zero to one when the state where a reactor is located enacted or implemented electricity market restructuring. However this variable is a noisy indicator for whether a reactor is still subject to rate-of-return regulation. For example, although California was one of the most aggressive states in deregulating its electricity market, the two nuclear power plants in California remained subject to regulation by the California PUC over financial matters during the study period,[33] as their owners did not discontinue the applications of SFAS No. 71 to its nuclear generating assets.[34] Moreover, in Iowa and Wisconsin where state-level restructuring has not been enacted, some nuclear reactors have been sold by regulated utilities to independent power producers and are no longer regulated by state PUCs.[35]

Davis and Wolfram (2012) and Hausman (2014) used another indicator, *DIVEST*, defined as an utility transferring nuclear power plants to unregulated subsidiaries or selling them to independent power producers, in their studies on the effects of divesture on nuclear plants' operation efficiency and safety. We consider this *DIVEST* variable to be less appropriate than the *PUC_DEREG* indicator used in our study. First, there is a potential lag in timing between removing a generation asset from regulatory rate-base and transferring it to unregulated companies.[36] For example, FirstEnergy, following restructuring legislation in Pennsylvania, removed its Beaver Valley nuclear plant from regulatory rate-base in 1998, but completed the transfer of plant ownership to its unregulated subsidiary in 2006. Second, there are five reactors that have been removed from rate-base but have never been divested by their owner utilities.[37]

V. EFFECT OF DEREGULATION ON NUCLEAR POWER UPRATES

V.1 Empirical Strategies

Multi-failure duration analysis with time-varying regressors

The first empirical strategy to investigate the impacts of deregulation on reactors' overall power uprates is a survival analysis with time-varying regressors. As shown in Table 1, more than half of the reactors in our data had one and only one power uprate application through the study period of 1991–2012, while the remainder had either zero or two or three uprate applications. Thus

33. One plant, the San Onofre plant, was retired prematurely due to the faulted steam generators on June 2013, a time that is beyond the paper's study period (1991–2012). Also see footnote 13.

34. Similarly, in the State of New York that had the state-wide electricity restructuring in 1996, the New York Public Service Commission (NYPSC) continued to allow electric utilities to keep their nuclear generation assets under rate-base regulation according to their individual restructuring plans, until the utilities themselves decided to sell nuclear plants to independent generators during 2000–2004.

35. These IPP producers are not regulated by state utilities. Instead, they entered into long-term purchase contracts with local utilities, and also have opportunities to sell power on organized markets. This gives them the same incentives for investment as nuclear producers in deregulated states.

36. When a generation asset is removed from rate-base, the utility becomes the residual claimant for the revenues accrued to the generation business; however, it may take some additional time for the utility to adjust its corporate structure and divest the asset.

37. These reactors include Fermi 2 (owned by Detroit Edison Company), North Anna Unit 1&2 and Surry Unit 1&2 (owned by Virginia Electric and Power).

we employ a multi-failure duration analysis that focuses on the years elapsed for reactor owners to apply for power uprates and analyze whether deregulation increases the hazard rate or likelihood of submitting applications. The multiple-failure Cox Proportional Hazard model involves time varying regressors, where the "hazard" or likelihood of reactor owners submitting a power uprate (of any type) application for reactor i in year t, given that they had not applied for uprates before year t, is assumed to be:

$$h_i(t) = h_{0,i}(t)\exp(M_{i,t-1}\beta + \varepsilon_{i,t}) \quad (1)$$

where $h_{0,i}(t)$ is the baseline hazard of reactor i, and

$$M_{i,t-1}\beta = \beta_1 PUC\_DEREG_{i,t-1} + \beta_2 W_{i,t-1} + \beta_3 X_{i,t-1} + \beta_4 Z_{i,t-1} + \gamma v_{t-1}$$

We use one-year lagged explanatory variables in the regressions, to account for the lag between deciding on an uprate investment and preparing and submitting an uprate application to NRC. The key explanatory variable is PUC_DEREG, whether the reactor is subject to deregulation. The time interval in the analysis is counted by years, staring from 1990; and year indicators are included in the regressions.

We include a number of time varying control variables that could potentially impact reactors' uprate decisions.[38] The first set of one-year lagged control variables $W_{i,\ t-1}$ are: (1) $Sales_{i,t-1}$, the yearly electricity sales (in MWh) in the state of the reactor i, to capture the impact of electricity demand on the reactor's decision on power uprates;[39] (2) $NGPrice_{i,t-1}$, the annually averaged natural gas citygate price (in dollar per thousand cubic feet) in the state of the reactor i,[40] to control for the possible impacts of natural gas price on power uprates, as new gas-fired plants could be substitutes of power uprates when plants decide to add generation capacity; (3) $CapacityMarket_{i,t-1}$, including $CapacityCreditMarket_{i,t-1}$ and $ForwardCapacityMarket_{i,t-1}$, which are binary indicators for whether capacity markets were implemented in the market where the reactor i was being operated, used to control for any potential impact of capacity markets on power uprates;[41] (4) $PUstatus_{i,t-1}$, binary indicators for reactor i's prior power uprate status, including $MURstatus_{i,t-1}$, $SPUstatus_{i,t-1}$ and $EPUstatus_{i,t-1}$ for whether the reactor i has already

38. Time-invariant reactor characteristics variables, including indicator of reactor type (BWR or PWRs), indicators of NRC regions, and reactor original licensed thermal power level (in MWt), could be added in the survival analysis, and the results are similar. These time invariant control variables are not needed for the two other econometric specifications that include reactor fixed effects.

39. Data is from the U.S. Department of Energy, Energy Information Administration, "Detailed Sales and Revenue Data by State, Monthly Back to 1990 (Form EIA-826)." Retrieved August 13, 2012 from http://www.eia.doe.gov/cneaf/electricity/page/sales_revenue.xls

40. Here we use the "Citygate Natural Gas Prices", for which the data is complete from 1990 to 2011. Another price, the "Electric Power Natural Gas Price", the price of gas used by electricity generators, might be more appropriate for the study, but the data is only available after 1997. The two prices are highly correlated (the correlation coefficient is 0.92) between 1997 and 2011 when both data are available. Although the city natural gas prices across states are highly correlated, there are still significant variations. For example, the correlation coefficient between the prices in California and in Vermont in our data is 0.70. Data source: U.S. Department of Energy, Energy Information Administration. "Natural Gas Prices." Retrieved August 30, 2013 from http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm.

41. $CapacityCreditMarket_{i,t-1}$ and $ForwardCapacityMarket_{i,t-1}$ are indicators for whether, for a reactor in a given year, there existed a capacity credit market (i.e. installed capacity market) and a forward capacity market, respectively. Information on implementation of capacity markets is collected from annual State of Market reports of relevant ISO/RTOs.

applied for a MUR, SPU or EPU, respectively, up to year $t-1$, which could affect the reactor's uprate decisions in year t.

We then include two reactor characteristic variables $X_{i,t-1}$ as additional controls. $Expiration_{i,t-1}$ is the number of years left before expiration of the license of reactor i in year $t-1$;[42] $LER_{i,t-1}$, the number of licensee event reports submitted to the NRC by reactor i in year $t-1$, is used to proxy the performance and reliability of the reactor.[43] The reliability of a reactor could be important in uprate decisions as plant systems and components need to be in good conditions and perform reliably to realize the full benefit of a power uprate (Hansen, 2007).

Finally we include a set of control variables $Z_{i,t-1}$ to capture other factors that might be relevant when a reactor i makes its uprate decisions. $Fleet_{i,t-1}$ is the number of nuclear reactors owned by the firm that owns reactor i in year $t-1$.[44] If a company has a number of reactors in its fleet, it may be able to take advantage of economies of scale. $Extension_{i,t-1}$ indicates whether the reactor also applied for life extension and license renewal within a five-year time window around year $t-1$.[45] Life extensions and power uprates could be related because (1) reactors may choose to perform power uprates and replace major equipment in order to support their plant life extension applications (Thomas, 2009); and (2) the benefits of power uprates would be more substantial with plant life extension (Kim, 2005).

Linear panel data regressions on probability of power uprates

Our second empirical specification involves Difference-in-Differences (D-D) linear probability regressions to identify the impacts of deregulation on reactors' power uprates. We compare the probability of applying for power uprates by owners of eventually-deregulated reactors after vs. before deregulation, using always-regulated reactors as the control group. Here we model the decision by owner of reactor i to apply for power uprates in a given year $t$as a binary decision (i.e. to apply or not to apply).

The econometric specification is:

$$Y_{i,t} = \beta_0 + \beta_1 PUC\_DEREG_{i,t-1} + \beta_2 W_{i,t-1} + \beta_3 X_{i,t-1} + \beta_4 Z_{i,t-1} + \upsilon_i + \nu_{t-1} + \varepsilon_{i,t} \qquad (2)$$

The dependent variable $Y_{i,t}$ is a binary variable, equal to one if a power uprate (MUR or SPU or EPU) is applied for by the reactor i in year t. It is a linear panel probability model, with individual reactor fixed effects υ_i and year dummies ν_{t-1} included.[46] The estimated coefficient for $PUC\_DEREG_{i,\ t-1}$ indicates how deregulation affects the probability of investing in any type of power uprates in a given year.

42. This control variable does not always decline by one from one year to the next for a certain reactor, as many reactors have obtained license extension from the NRC during the period of our analysis.

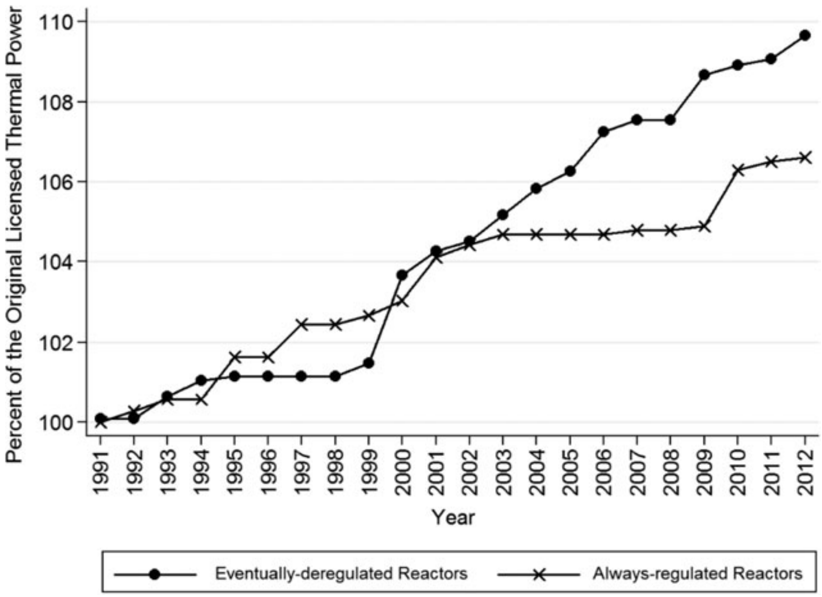
43. A smaller number of licensee events reports indicate higher reactor reliability. Licensee event reports data was retrieved from the NRC Licensee Event Report Search (LERSearch) system at https://lersearch.inl.gov/Entry.aspx.

44. The data on the number of reactors owned by firms was primarily based on SEC 10-K annual filings of reactors involved, and cross referenced with data from EIA-860 Annual Electric Generator Report. For robustness, we also replaced this control variable with "the number of same type of reactors (i.e. BWRs or PWRs)", and the regression results still hold.

45. Data source: U.S. NRC. "Status of License Renewal Applications and Industry Activities." Retrieved August 30, 2012 from http://www.nrc.gov/reactors/operating/licensing/renewal/applications.html

46. The reason that we employ panel data linear probability models rather than panel data Probit or Logit regressions here is that estimation of these nonlinear models sometimes do not converge, possibly due to a large number of reactor fixed effects and year indicators.

Figure 2: Reactor thermal power level (as percent of the Original Licensed Thermal Power), eventually-deregulated versus always-regulated reactors



Note: The licensed maximum thermal power level of an average reactor in each year *t* (between 1991 and 2012) accounts for increase in reactor power due to power uprates that an reactor has applied for up to year *t* and is scaled on the original licensed thermal core power. Here we focus on the 76 investor-owned reactors whose owners had not applied for any power uprate (i.e. SPUs, the only type of power uprate available) prior to 1991 (the starting year of the study period) and also did not apply for the same type of power uprate more than once, separating the 44 eventually-deregulated reactors from the 32 always-regulated reactors.

Linear panel data regressions on reactor thermal power level

Finally we employ a D-D strategy to investigate whether the reactor thermal power level of an eventually-deregulated reactor significantly increases after deregulation, using always-regulated reactors as the control group. The econometric specification is the same as Equation (2), with the dependent variable $Y_{i,t}$ being the maximum reactor thermal power level for a reactor *i* in year *t*. The variable accounts for the increase in power level due to power uprates that the reactor has applied for by year *t*, scaled as a percent of its original licensed thermal power. The coefficient β_1 for $PUC\_DEREG_{i,\ t-1}$ indicates the percentage increase in thermal power (relative to the original licensed thermal power) through power uprates after an average reactor is deregulated.

V.2 Graphical Evidence

The baseline analyses focus on the 76 investor-owned reactors whose owners had not applied for any power uprate (i.e. SPUs, the only type of power uprate available) prior to 1991 (the starting year of the study period) and also did not apply for the same type of power uprate more than once. In Figure 2 we plot, for the 44 eventually-deregulated reactors and 32 always-regulated reactors separately, the licensed maximum thermal power level of an average reactor in each year between 1991 and 2012, accounting for the increase in a reactor's core power level due to power uprates it had applied for up to year *t*and scaled on (as a percent of) the original licensed thermal power level. The figure exhibits a clear positive correlation between deregulation and power uprates. Between 1991 and 1994, the prior-deregulation period, owners of reactors in the two groups applied a similar amount of power uprates. Between 1995 and 1998 when many reactors were in the transition to deregulation, owners of eventually-deregulated reactors essentially stopped uprate applications, whereas owners of always-regulated ones still applied for uprates. Since 1999 when deregulation in most states with market restructuring had either been enacted or become effective, owners of these deregulated reactors have been more likely to submit uprate applications and on balance their reactor power levels have been higher than those of always-regulated ones since 2004.

The increase in deregulated reactors' thermal power level in the first few years following 1999, in particular the jump in 2000, could reflect some make-up activities, given the pause in uprate applications during the transition period of 1995–1998. However, owners of deregulated reactors have been applying for more power uprates than that of always-regulated reactors throughout the post-deregulation period of 1999–2007. Since the financial crisis in 2008, deregulated reactors have been similar with always-regulated reactors in applying for power uprates.

V.3 Empirical Results

Baseline results

Panel A of Table 3 presents the baseline results.[47] Columns 1–3 involve multiple-failure Cox Proportional Hazard regressions.[48] We focus on the hazard ratio, the exponential of the estimated coefficient β_1 for the key explanatory variable, $PUC\_DEREG_{i,\ t-1}$, in Equation (1). A hazard ratio of greater than one indicates an increase in the probability of applying for a power uprate after the reactor is deregulated (a change from zero to one in $PUC\_DEREG_{i,\ t-1}$), conditional on that the owners have not yet applied for any uprates up to year *t*. The results in Columns 1–3 suggest that the hazard ratio of applying for power uprates more than doubles after deregulation.[49]

Columns 4–6 of Table 3 involve panel linear probability regressions, as specified in Equation (2). The results show that after deregulation the probability of investing in power uprates increases by about ten percentage points, relative to always-regulated reactors. Columns 7–9 study

47. The standard errors in Table 3 are clustered at the reactor level, for the following reasons. First, two reactors at the same plant site do not necessarily have the same design. For example, the two reactors in the Arkansas Nuclear One plant (AR) were designed by two vendors (Babcock & Wilcox, and Combustion Engineering); to date, the plant only had EPUs on the Combustion Engineering designed reactor. Second, even if two reactors in a plant are of the same design, they might be constructed and go into commercial operation at different points in time and thus were with different vintages. For instance, the two reactors with the same design in the Salem plant (NJ) went into commercial operation in 1977 and 1981, respectively. Only one reactor applied for a SPU in 1986. Third, even for two side-by-side reactors in a plant that are of the same design and went into commercial operation at the same time, the NRC still requires separate evaluation of power uprate feasibility for each (Thomas, 2009); and thus the owner may apply for a power uprate for one but not the other. For instance, the two reactors in the California's Diablo Canyon plant are both designed by Westinghouse and went into commercial operation in mid-1980s. However the owner of Diablo Canyon only decided to perform a SPU in one reactor. For robustness checks, we also tried clustering either at the plant level or at the plant/reactor type level (i.e. reactors of the same type in a plant). The standard errors remain similar, lending support to the notion that power uprates are likely individual reactor specific.

48. In this specification, we assume that a reactor become "at risk" of applying for power uprates since 1990, and we reset the baseline hazard $h_{0,i}(t)$ whenever a reactor applied an uprate of any type.

49. Table D1 of Appendix D reports estimates of hazard ratio for all control variables under Cox Proportional Hazard regressions.

Table 3: Deregulation and Overall Power Uprates

	Cox PH Regressions on Power Uprates			Linear Probability Panel Regressions on Power Uprates			Linear Panel Regressions on Reactor Thermal Power (% of the original licensed power level)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A: All observations, 1991-2012									
PUC_DEREG	2.855***	2.877***	2.496***	.135***	.121***	.113***	2.119***	2.097***	1.877***
	(.786)	(.798)	(.724)	(.0323)	(.0329)	(.0345)	(.486)	(.484)	(.473)
Panel B: Excluding observations between 1995 and 2000									
PUC_DEREG	2.363***	2.478***	2.356**	.0844*	.0781	.0679	2.217***	2.279***	1.980***
	(.760)	(.823)	(.799)	(.0464)	(.0475)	(.0518)	(0.599)	(0.610)	(0.623)
Panel D: Excluding observations between 2008 and 2012									
PUC_DEREG	2.909***	2.935***	2.753***	.138***	.120***	.113***	1.826***	1.759***	1.660***
	(.788)	(.798)	(.824)	(.0351)	(.0368)	(.0375)	(.468)	(.474)	(.463)
Electricity Demand (Sales)	X	X	X	X	X	X	X	X	X
Natural Gas Price (NGPrice)	X	X	X	X	X	X	X	X	X
Capacity Market (CapacityMkt)	X	X	X	X	X	X	X	X	X
Prior Uprate Status (PUstatus)	X	X	X	X	X	X	X	X	X
Reactor Characteristics (X)		X	X		X	X		X	X
Commercial Decisions (Z)			X			X			X

Note: The table reports results for *PUC_DEREG* in Equations (1) and (2) in Section 5. The regressions focus on the 76 investor-owned reactors that their owners had not applied for any power uprate (i.e. SPUs, the only type of power uprate available) prior to 1991 (the starting year of the study period) and that did not apply for the same type of power uprate more than once.). Dependent variables in columns (1) to (6) are binary indicators of applying for any type of power uprates; dependent variables in columns (7) to (9) are the maximum reactor thermal power scaled on original licensed core thermal limit (in %), reflecting changes due to power uprates. In columns (1) to (3), we report hazards ratio estimates of *PUC_DEREG* in Equation (1) by running Cox Proportional Hazard regressions, with year fixed effects where we assume all reactors become "at risk" of undertaking power uprates since 1991. An estimate of hazard ratio greater than one suggests positive impacts. In columns (4) to (6) and columns (7) to (9), we report coefficient estimates of *PUC_DEREG* in Equation (2), for probability of applying for power uprates and the maximum reactor thermal power, respectively, by running panel data regressions, with reactor and year fixed effects. Standard errors in parentheses clustered at the reactor level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

the change in reactors' maximum thermal power level and show that on average deregulation incentivizes reactors to add additional 1.9 to 2.1 percent of the original reactor thermal power through power uprates, compared to always-regulated ones.[50] Thus, the results from all the three econometric models consistently suggest significantly positive impacts of deregulation on power uprates.[51]

The results on impacts of potential economy of scale (*FLEET*) and capacity markets (*CapacityMarket*) on power uprates are also noteworthy. In the three specifications, we find a small but significantly positive effect of economy of scale (*FLEET*) on power uprates, suggesting that power uprates may be highly individual reactor specific. In contrast, capacity markets had somewhat negative impacts on uprate applications (See Table D2 in Appendix D).

Robustness checks

Concerning the pause in applying for uprates during transition. As discussed above, there was a period in the mid-1990s where owners of reactors in soon-to-be restructured states stopped applying for power uprates, perhaps due to uncertainties about what regulatory regime would be imposed. Panel B of Table 3 tests whether the results are driven by the pause in applying for power uprates during the transition period of 1995–1998 and any "rebound" in applications by now-deregulated reactors immediately following deregulation. We take out the observations in the window around deregulation (the period of 1995–2000), and re-run the regressions. The results for the hazard ratio of applying for power uprates and for the reactor thermal power level, as shown in Panel B of Table 3, are very similar to the baseline results and suggest a consistently positive and significant effect of deregulation on power uprates.

Concerning the 2008 financial crisis. The U.S. went through the financial crisis and economic downturn during this period, which might have differential impacts on nuclear reactors with different regulatory status. In Panel C of Table 3, we exclude the observations during 2008–2012. The results again show consistently positive and significant coefficients for the key variable *PUC_DEREG* across all specifications.

Additional robustness checks. We conduct some additional robustness checks: (1) controlling for financing of power uprates;[52] and (2) including the 15 reactors that either had power uprates (SPUs) prior to 1991 or applied for the same type of uprate twice and thus are excluded in the baseline regressions. The results (available from the authors) are consistent with the baseline results.

Testing alternative indicators of deregulation

We also compare the two alternative indicators for reactor deregulation, *DIVEST* and *STATE_RESTURCTURE*, respectively, in place of our proposed indicator, *PUC_DEREG*. Table

50. Our results are similar in magnitude to those presented in Pane A of Table 7 in Davis and Wolfram (2012).

51. We also used the current-year values (instead of their one-year lags) for all control variables and focus on power uprates between 1991 and 2011 (natural gas price data in 2012 is not complete). The results are similar. We also replaced the one-year lagged electricity demand ($Sales_{i,t-1}$) and natural gas price ($NGPrice_{i,t-1}$) with the averaged value of the last three years ($t-1$, $t-2$ and $t-3$), and focus on power uprates between 1993 to 2012 (electricity demand data is only available from 1990). The results hold true.

52. Power uprates such as SPUs and EPUs are capital-intensive and expensive projects, and how they are financed could be an important factor for deregulated reactors to decide on power uprates investment. We include two additional control variables in the regressions to control for the financial well-being of the company owning the reactor of interest: (1) the ratio of net cash flow provided by operating activities to total assets; and (2) the ratio of cash and cash equivalent on hand to the total assets.

4 suggests that the coefficients for *DIVEST* and *STATE_RESTURCTURE*, are smaller in magnitude (particularly with the latter) and less significant, compared to the results in Panel A of Table 3. The results suggest these two alternatives, though used in other studies, are noisier indicators than *PUC_DEREG* for the purpose of our study.

Addressing potential selection bias

The major difference between eventually-deregulated and always-regulated reactors is their locations, as deregulation of reactors mostly followed electricity market restructuring at the state level.[53] If state-level decisions about restructuring were influenced by some factors that are correlated with the trends in reactor capacity investments, there might be an "omitted variable" problem which would threaten the identification of a causal relationship between deregulation and power uprate applications.

We first posit that a selection on state-level restructuring would likely introduce bias against our results. State-level restructuring decisions were largely driven by high electricity prices and liberal politics at the state level (White 1996). The relatively high electricity prices in those states was partly due to excessive investment in nuclear power that were often associated with cost overruns leading to huge "stranded costs" (Borenstein and Bushnell, 2000). In this case, we would expect that nuclear reactors in deregulated states, given their over-investment in nuclear capacity in earlier years, would, *ceteris paribas*, be less likely to undertake power uprates.

We then consider the several cases where decisions on reactor deregulation were made at the reactor level, separate from state level market restructuring. We conduct several robustness checks, as laid out in Table 5, following Davis and Wolfram (2012). First, despite state level restructuring activities in California, the four California reactors (in two nuclear plants) continued to be subject to regulation on financial matters by California PUC during the study period, raising concerns about selection. Excluding the four reactors from the sample, the results for *PUC_DEREG* are essentially unchanged (Panel A of Table 5). Second, in the state of New York, after the state-wide electricity restructuring took place in 1996, the New York Public Service Commission continued to allow electric utilities to keep their nuclear generation business in rate-base regulation, until the utilities themselves decided to sell their nuclear plants to independent generators between 2000 and 2004. This also raises possible concerns of selection bias. Taking out all the reactors in New York, we find that the estimated coefficients for *PUC_DEREG* remain largely the same (Panel B of Table 5).

Third, Iowa and Wisconsin did not deregulate their electricity markets, but the electric utilities there have divested all of their nuclear reactors. When these reactors are excluded from the sample, the coefficients for *PUC_DEREG* are similar (Panel C of Table 4). Finally, in Michigan where electricity restructuring was enacted, one reactor was divested (and deregulated), and among the other three reactors still owned by electric utilities, only one was removed from the rate-base and the other two have been subject to cost-based regulation. When we exclude the four Michigan reactors, the results are essentially identical (Panel D of Table 5). All together, these results reassure

53. In Appendix C, we conduct an analysis on covariate balance between eventually-deregulated and always-regulated reactors, distinguished by their reactor types (BWRs or PWRs). Both eventually-deregulated BWRs and PWRs are similar to the always-regulated counterparts, in terms of original licensed thermal power (in MWt) and reactor age. The major difference is their location.

Table 4: Tests of Alternative Indicators of Reactor Deregulation

	Cox PH Regressions on Power Uprates			Linear Probability Panel Regressions on Power Uprates			Linear Panel Regressions on Reactor Thermal Power (%)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A: Using the indicator of plant divestiture									
DIVEST	2.179**	2.201**	1.538	.0795***	.0648**	.0492	1.882***	1.903***	1.635***
	(.732)	(.745)	(.633)	(.029)	(.0322)	(.0376)	(.522)	(.529)	(.595)
Panel B: Using the indicator of state level deregulation									
STATE_RESTRUCTURE	1.335	1.344	1.177	.0398	.0212	.0158	.572	.520	.401
	(.342)	(.345)	(.306)	(.0293)	(.0291)	(.0289)	(.398)	(.408)	(.403)
Electricity Demand (Sales)	X	X	X	X	X	X	X	X	X
Natural Gas Price (NGPrice)	X	X	X	X	X	X	X	X	X
Capacity Market (CapacityMkt)	X	X	X	X	X	X	X	X	X
Prior Uprate Status (PUstatus)	X	X	X	X	X	X	X	X	X
Reactor Characteristics (X)		X	X		X	X		X	X
Commercial Decisions (Z)			X			X			X

Note 1: We replace *PUC_DEREG* with *DIVEST* and *STATE_RESTRUCTURE* in Equations (1) and (2) of Section 5, respectively. The regressions focus on the 76 investor-owned reactors that had not applied for any power uprate (i.e. SPUs, the only type of power uprate available) prior to 1991 (the starting year of the study period) and that did not apply for the same type of power uprate more than once. Dependent variables in columns (1) to (6) are binary indicators of applying for any type of power uprates; dependent variables in columns (7) to (9) are the maximum reactor thermal power scaled on original licensed core thermal limit (in %), reflecting changes due to power uprates. In columns (1) to (3), we report hazards ratio estimates of *DIVEST* and *STATE_RESTRUCTURE* in Equation (1) by running Cox Proportional Hazard regressions, with year fixed effects where we assume all reactors become "at risk" of undertaking power uprates since 1990. An estimate of hazard ratio greater than one suggests positive impacts. In columns (4) to (6) and from columns (7) to (9), we report coefficient estimates of *DIVEST* and *STATE_RESTRUCTURE* in Equation (2), for probability of applying for power uprates and the maximum reactor thermal power, respectively, by running panel data regressions, with reactor and year fixed effects. Standard errors in parentheses clustered at the reactor level..*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Note 2: Our results with *DIVEST* in columns (7) to (9) are largely consistent with Davis and Wolfram (2012) that suggest "a relationship between divesture and increase in generating capacity (due to uprates)". Their estimated coefficients for *DIVEST* are of similar magnitude as ours but less significant, likely because their study involves a different analysis period and a slightly different sample of reactors.

Table 5: Addressing Concerns About Potential Selection Bias

	Cox PH Regressions on Power Uprates			Linear Probability Panel Regressions on Power Uprates			Linear Panel Regressions on Reactor Thermal Power (%)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A: Exclude California									
PUC_DEREG	2.675***	2.686***	2.354***	.133***	.114***	.108***	2.093***	2.060***	1.852***
	(.792)	(.802)	(.739)	(.0331)	(.0338)	(.0356)	(.500)	(.501)	(.491)
Panel B: Exclude New York									
PUC_DEREG	2.422***	2.414***	2.202**	.122***	.108***	.104***	2.052***	2.020***	1.802***
	(.725)	(.731)	(.677)	(.0352)	(.0356)	(.0373)	(.527)	(.528)	(.504)
Panel C: Exclude Iowa and Wisconsin									
PUC_DEREG	2.740***	2.750***	2.433***	.129***	.110***	.104***	1.856***	1.793***	1.627***
	(.762)	(.770)	(.721)	(.0347)	(.0356)	(.0367)	(.484)	(.477)	(.471)
Panel D: Exclude Michigan									
PUC_DEREG	4.354***	4.358***	3.752***	.157***	.143***	.136***	2.403***	2.360***	2.144***
	(1.282)	(1.286)	(1.173)	(.0312)	(.0321)	(.0328)	(.509)	(.506)	(.489)
Electricity Demand (Sales)	X	X	X	X	X	X	X	X	X
Natural Gas Price (NGPrice)	X	X	X	X	X	X	X	X	X
Capacity Market (CapacityMkt)	X	X	X	X	X	X	X	X	X
Prior Uprate Status (PUstatus)	X	X	X	X	X	X	X	X	X
Reactor Characteristics (X)		X	X		X	X		X	X
Commercial Decisions (Z)			X			X			X

Note: This table reports results for *PUC_DEREG* in Equation (1) and (2) in Section 5, by excluding reactors in states of California, New York, Iowa and Wisconsin, and Michigan respectively from the 76 reactors during 1991–2012 (see Note in Table 3). Dependent variables in columns (1) to (6) are binary indicators of applying for any type of power uprates; dependent variables in columns (7) to (9) are the maximum reactor thermal power scaled on original licensed core thermal limit (in %), reflecting changes due to power uprates. In columns (1) to (3), we report hazards ratio estimates of *PUC_DEREG* in Equation (1) by running Cox Proportional Hazard regressions, with year fixed effects where we assume all reactors become "at risk" of undertaking power uprates since 1990. An estimate of hazard ratio greater than one suggests positive impacts. In columns (4) to (6) and columns (7) to (9), we report coefficient estimates of *PUC_DEREG* in Equation (2), for probability of applying for power uprates and the maximum reactor thermal power, respectively, by running panel data regressions, with reactor and year fixed effects. Standard errors in parentheses clustered at the reactor level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

us that the correlation between reactor deregulation and investing in power uprates is not driven by selection bias.

VI. DEREGULATION AND CHOICES OF POWER UPRATES: BWR VERSUS PWR

So far we have shown that deregulation incentivizes owners of nuclear reactors to undertake power uprates. In this section, we investigate whether, after deregulation, the two different types of reactors, BWRs and PWRs, differ in terms of which types of uprates are more likely to be applied for. As discussed above, our hypothesis here is that owners of deregulated PWRs are more likely to undertake SPUs or MURs, as PWRs have inherent technical limitations and disadvantages (in particular related to steam generators) in undertaking EPUs. Owners of deregulated BWRs, however, are expected to be more likely to apply for EPUs because EPUs provide an economic way to maximize reactor generation capacity and thus revenue and profit.

VI.1 Empirical Specifications

Duration analysis with time-varying regressors

Similar to our analyses on the impacts of deregulation on overall power uprates, we first run a Cox Proportional hazard regression model (with time varying regressors) for applying for MURs, SPUs and EPUs separately.[54] We assume that the "hazard" or probability of the owners of reactor i applying for a power uprate of type k at year t (given that it had not applied for this type of uprate before) is:

$$h_i^k(t) = h_{0,i}(t)\exp(N_{i,t-1}\beta + \varepsilon_{i,t}) \tag{3}$$

where k denotes MUR, SPU or EPU; and

$$N_{i,t-1}\beta = \beta_1 PUC\_DEREG_{i,t-1}{*}BWR_i + \beta_2 PUC\_DEREG_{i,t-1}{*}PWR_i$$
$$+ \beta_3 W_{i,t-1} + \beta_4 X_{i,t-1} + \beta_5 Z_{i,t-1} + v_{i,t-1}$$

The two key variables of interest are $PUC\_DEREG_{i,t-1}{*}BWR_i$ and $PUC\_DEREG_{i,t-1}{*}PWR_i$, where BWR_i and PWR_i indicate whether a reactor i is a BWR or PWR, and $PUC\_DEREG_{i,t-1}$ indicates whether the reactor is deregulated in year $t-1$.[55] The coefficients on these variables for a power uprate of type k indicates whether deregulated BWRs and PWRs are more likely to undertake an uprate of type k, relative to always-regulated reactors. We also include the control variables discussed in Section 5.[56]

54. Alternatively, we employed Competing Risks regressions that model the duration (years elapsed) that a nuclear reactor has waited to choose a specific type of power uprate, among other "competing" options (Fine and Gray, 1999), and the results are qualitatively similar. A Competing Risks model assumes that a reactor can only undertake one type of uprate, which does not hold here.

55. The time-invariant indicator (BWR_i or PWR_i) is not included in Equation (3), because adding them yields no convergence in some regressions.

56. All explanatory variables here are one-year lagged, to account for the lag between deciding to undertake uprates and applying to the NRC.

Linear panel data regressions on probability of each type of power uprates

We then run three separate panel data linear probability regressions to identify the impacts of deregulation on the probability of a reactor applying for a power uprate of type k (a MUR, SPUs or EPU). The regressions are specified as follows:

$$Y_{i,t}^{k} = \beta_0 + \beta_1 PUC\_DEREG_{i,t-1} {*} BWR_i + \beta_2 PUC\_DEREG_{i,t-1} {*} PWR_i + \beta_2 W_{i,t-1} + \beta_3 X_{i,t-1} + \beta_4 Z_{i,t-1} + \upsilon_i + \nu_{t-1} + \varepsilon_{i,t} \quad (4)$$

Where independent variables $Y_{i,t}^{MUR}$, $Y_{i,t}^{SPU}$ and $Y_{i,t}^{EPU}$ are binary indicators for whether a reactor i submitted a MUR, a SPU or an EPU application, respectively, in year t. The two variables of interest are $PUC\_DEREG_{i,t-1}{*}BWR_i$ and $PUC\_DEREG_{i,t-1}{*}PWR_i$, and the estimated coefficients indicate how deregulation affects the probability that a BWR and a PWR decide to invest in a specific type of power uprate respectively.

Linear panel data regressions on reactor power level due to each type of power uprates

Finally we run three separate panel data regressions to investigate if the reactor thermal power level of an eventually-deregulated reactor significantly increases after deregulation due to the application of a power uprate of type k (a MUR or SPU or EPU). The specifications are the same as Equation (4), with dependent variables, $Y_{i,t}^{MUR}$, $Y_{i,t}^{SPU}$ and $Y_{i,t}^{EPU}$, being the reactor thermal power level of the reactor i in year t, which accounts for the increase in core thermal power due to a power uprate of type k (a MUR or SPU or EPU) that the reactor has applied for by year $t$and scaled as a percent of its original licensed thermal power. The coefficients for $PUC\_DEREG_{t-1}{*}BWR_i$ and $PUC\_DEREG_{i,t-1}{*}PWR_i$ suggest whether deregulation incentivizes BWRs and PWRs to undertake a MUR, a SPU, or an EPU, respectively.

V.2 Empirical Results

Table 6 presents the results on the choices of power uprates by owners of deregulated BWRs versus deregulated PWRs.[57] Here the period of analysis is 1995 to 2012 because all the three uprate choices became available in 1995. We focus on the 62 reactors that did not have power uprates before 1995 and did not have the same type of uprate more than once during the study period.

In columns 1–3 of Table 6 we report estimates of hazard ratio of applying for MURs, SPUs and EPUs respectively, by running Cox PH regressions for the three types of uprates separately. The results show that for the hazard ratios of choosing MURs and SPUs significantly increase for deregulated PWRs, but not for deregulated BWRs. The hazard ratio of applying for EPUs, however, goes up significantly for deregulated BWRs, but changes insignificantly for deregulated PWRs.

In columns 4–6, we run three separate linear probability models, estimating the effects of deregulation on the probabilities of investing in MURs, SPUs or EPUs, by BWRs and PWRs, respectively. The probabilities of applying for MURs and SPUs significantly increase for deregu-

57. The standard errors in Table 6 are clustered at the reactor level. As explained earlier (see footnote 46), power uprate decisions are likely to be made at the reactor level, rather than at the plant level.

Table 6: Deregulation and Choices of Power Uprates, by BWRs Versus PWRs

	Cox PH Regressions on Each Type of Power Uprates			Linear Probability Regressions on Each Type of Power Uprates			Linear Panel Regressions on Reactor Thermal Power (% of the original licensed power level), due to each type of uprates		
	(1) MUR	(2) SPU	(3) EPU	(4) MUR	(5) SPU	(6) EPU	(7) MUR	(8) SPU	(9) EPU
PUC_DEREG * BWR	.781	2.254	5.838**	-.0507	.0325	.0982***	-0.108**	.265	3.244***
	(.556)	(2.199)	(5.147)	(.0320)	(.0397)	(.0368)	(0.0451)	(.198)	(.986)
PUC_DEREG * PWR	3.426**	4.634***	1.615	.0729**	.136***	.0491	.0342	.838***	1.268*
	(1.659)	(2.417)	(1.182)	(.0289)	(.0351)	(.0337)	(.0495)	(.0201)	(.712)
Electricity Demand (Sales)	X	X	X	X	X	X	X	X	X
Natural Gas Price (NGPrice)	X	X	X	X	X	X	X	X	X
Capacity Market (CapacityMkt)	X	X	X	X	X	X	X	X	X
Prior Uprate Status (PUstatus)	X	X	X	X	X	X	X	X	X
Reactor Characteristics (X)	X	X	X	X	X	X	X	X	X
Commercial Decisions (Z)	X	X	X	X	X	X	X	X	X

Note: In this table we focus on 62 reactors that did not apply any power uprates before 1995 and that did not apply the same type of power uprate more than once. The study period is 1995–2012. Dependent variables in columns (1) to (6) are binary choices for whether applying for a MUR, a SPU or an EPU respectively, in year *t*. In columns (7) to (9) dependent variables are maximum reactor thermal power level scaled on original licensed core thermal limit (in %), reflecting changes due to a MUR, SPU or EPU separately. In columns (1) to (3), we report hazards ratio estimates of *PUC_DEREG*BWR* and *PUC_DEREG*PWR* in Equation (3) of Section 6, by running Cox Proportional Hazard regressions separately on the three types of power uprates, with year fixed effects and assuming all reactors become "at risk" of applying power uprates since 1995. An estimate of hazard ratio greater than one suggests positive impacts. In columns (4) to (6) and (7) to (9), we report coefficient estimates corresponding to Equation (4) in Section 6, by running three panel data regressions (with reactor and year fixed effects) separately. Standard errors in parentheses clustered at the reactor level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

lated PWRs, but not for deregulated BWRs. On the other hand, the probability of investing in EPUs significantly goes up for deregulated BWRs, but not for deregulated PWRs.

In columns 7–9, we run three separate regressions estimating the effects of deregulation on reactor thermal power level (scaled on original licensed thermal power) through MURs, SPUs and EPUs, respectively, for BWRs and PWRs separately. The increase in reactor thermal power level due to SPUs is significant for deregulated BWRs, but not for deregulated PWRs. However, deregulated PWRs significantly increase their thermal power level through EPUs.[58]

Together, the results in Table 6 support our hypothesis that deregulation provides incentives for both BWRs and PWRs to invest in power uprates, and the two types of reactors differ in their choices of uprate types.[59,60]

VII. POLICY IMPLICATIONS AND CONCLUSIONS

Economic theories suggest that market deregulation provide incentives for firms to make efficient and carefully calculated investment decisions to maximize “uncapped” profits. This paper examines whether electricity deregulation in the U.S. has incentivized reactor owners to undertake power uprates that are cost effective and profitable investments in generation capacity. Using data on power uprate applications submitted to the NRC by investor-owned nuclear reactors from 1991 to 2012, we find that owners of deregulated reactors are more likely to apply for power uprates than their counterparts of regulated reactors. In particular, owners of deregulated BWR reactors are more likely to undertake Extended Power Uprates (EPUs) that involve a total upfront cost of often over $100 million and could increase reactor thermal power by up to 20 percent. In contrast, owners of deregulated PWR reactors, for which EPUs are more technically challenging, expensive and risky, tend to choose SPUs or MURs that add smaller amount of reactor thermal power but are less risky and less expensive. These results suggest that deregulation and competition incentivize firms to make carefully considered investments in generation capacity, taking into consideration project profitability, upfront cost and risks and their plant technology characteristics.

Our study, by providing a novel perspective on electricity market deregulation and firm incentives in investing, has important policy implications for the future development of nuclear power in competitive markets. Indeed, with increasing costs to comply with new regulatory requirements (in the aftermath of the Japanese Fukushima accident in 2011) and competition from gas-fired plants (due to significant drop in gas price following shale gas production), some deregulated utilities have informed the NRC to suspend or withdraw their applications for new full-size reactors.[61] At the same time, smaller modular reactors (SMRs), which are newer, simpler and standardized designs that have yet been commercialized, have been promoted as promising alternatives for expensive full-size reactors.[62] Some claims that SMRs offer a number of advantages

58. It is also noteworthy that after deregulation BWRs seem to be less likely to applying for MURs as suggested by column 7 in Table 6.

59. In terms of control variables, we have consistently significant and negative coefficients for $SPUstatus_{i,t-1}$ and $EPUstatus_{i,t-1}$ for choosing SPU and EPU respectively in regressions from columns (1) to (6). Coefficients of other control variables are inconclusive across specifications.

60. We conduct several robustness checks, including addressing possible concerns of selection bias, concerning financing of power uprates, and including all reactors. The results largely hold (available from the authors).

61. Exelon, for instance, decided to withdraw its application for building two reactors in Victoria County, Texas. See World Nuclear News. (2012, August 29) “Victoria defeated by cheap gas.”

62. SMRs are designed to provide a generation capacity of 45 to 225 MWe and incur a initial capital cost of hundreds of billions of dollars.

including smaller upfront capital cost, shorter construction time and being safer (underground) and more flexible in terms of plant location and grid requirement (Guinnessy, 2010; Vujic et al., 2012). Since SMRs have generation capacity and upfront cost that are to some extent comparable to those of SPUs and EPUs, our study on power uprates suggests that although SMRs might potentially attractive, the advantages of SMRs need to be demonstrated and the risks to be better understood, in order for deregulated firms, motivated to undertake profitable investments, to adopt the technology.[63]

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63. In 2013 DOE awarded the first $79 million to a consortium of an industry group and the Tennessee Valley Authority, to commercially demonstrate the first SMR by 2022. See World Nuclear News (2013, April 16). "SMR funding signed, sealed and delivered."

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