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# Mandate a Man to Fish?: Technological Advance in Cooling Systems at U.S. Thermal Electric Plants

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**ABSTRACT**

Steam-based electrical generating plants use large quantities of water for cooling. The potential environmental impacts of water cooling systems have resulted in their inclusion in the Clean Water Act's (CWA) Sections 316(a), related to thermal discharges and 316(b), related to cooling water intake. The CWA mandates a technological standard for water cooling systems. This analysis examines how the performance-adjusted rates of thermal emissions and water withdrawals for cooling units have changed over their vintage and how these rates of change were impacted by imposition of the CWA. Though technology standards are believed to hinder technological progress, results show that progress occurred for cooling systems installed after the CWA and no progress occurred previous to it.

*JEL* **classifications: Q52, Q40, L51**
**Keywords:** Water Withdrawals, Thermal Pollution, Innovation, Environmental Policy

## I. Introduction

Cooling systems at thermal generating plants use vast amounts of water to cool steam; increasing pressure gradients across turbines and allowing generation of greater amounts of electricity from a fixed amount of fuel. According to the International Energy Agency (2012), it is estimated that 15% of the world's water withdrawals are used to cool power plants. The number is around 41% in the U.S. (Kenny et. al., 2009). Older cooling systems typically withdraw water and then discharge it whereas newer technology recirculates water, using it repeatedly, thus reducing the withdrawals and discharges. The withdrawal of cooling water negatively impacts aquatic organisms and discharge of large volumes of warm water (known as thermal pollution) can cause significant environmental damage. As a result, cooling systems are regulated by the Clean Water Act (CWA).

The CWA has mandated use of recirculating cooling systems as the preferred technology for addressing these environmental concerns, but allows the use of so-called once-through systems where it is demonstrated that their use will not generate additional detrimental environmental impacts. We investigate the effects of the CWA's technology-based regulatory approach on the rate of technological advance in both the favored technology, recirculating systems, and the disadvantaged technology, once-through systems. The impact of regulation on technological advance is an important consideration in energy and environmental issues (Kneese and Schultz, 1978). Our investigation corrects for the potential selection bias that results from CWA allowance of once-through systems if they can meet the environmental impacts of recirculating systems. A hedonic model of water withdrawal/thermal emissions is estimated to determine their association with power plant and water cooling system characteristics, specifically vintage (year installed), type of water cooling system, and regulation status. Our question is whether, correcting for the performance of the associated plant, there has been progress in the form of reduced thermal emissions and/or water withdrawals and whether differential progress has occurred due to the structure of the CWA. This question is important both because it examines the general relationship between technology-based regulation and technological progress and because regulation of cooling water systems has been reconsidered recently by the U.S. Environmental Protection Agency (EPA) due to a U.S. Supreme Court decision.

Our findings reveal that most of the technological advancement in cooling systems has occurred since the CWA was implemented. For both water withdrawals (regulated under Section 316(b) of the CWA) and thermal pollution discharges (regulated under Section 316(a) of the CWA), cooling system performance-adjusted environmental impacts were getting worse until the time of the CWA. Since then, the performance-adjusted environmental impact is improving about 4-8% per vintage of cooling water systems. This result is consistent across a number of specifications including those that control for the selection bias in use of once-through systems given the CWA allowance to use them when environmental impacts are similar to those of recirculating systems.

The concern over the impacts of power plants on waterways, specifically with regard to withdrawals, is a contemporary policy issue given a 2009 decision by the U.S. Supreme Court in the *Entergy v. Riverkeeper* case. The CWA had required the EPA to devises rules surrounding the use of water cooling technology for existing and new plants. While the EPA was able to set a rule that favored the use of recirculating cooling systems for new power plants, it was not able to set a rule for existing power plants due to legal and political action. The EPA issued a rule for existing power plants in April 2014 given the *Entergy v. Riverkeeper* case.

Further, our work addresses a lingering question in the field. A lot of environmental regulation is technology-based. That is, regulations are defined based on the performance of one type of technology and, as such, application of this technology is de facto satisfaction of those regulations. A large literature has generally shown that these technology standards have tend to offer poor incentives for technological advance. In practice, the empirical evidence on incentives for technological advance is small thus this analysis contributes to finding an answer to this important question.

## II. Background

Thermal generating plants use a heat source, typically fossil fuels or nuclear reactions, to boil water into steam that is then used to spin turbines and generate electricity.[1] Cooling systems play an invaluable role in the generation process by cooling the steam in post-turbine condensers, thus increasing the pressure gradient across the turbine and increasing the amount of electricity generated from a fixed amount of fuel. The by-product of this process is a significant increase in cooling water temperature, typically 17˚F for fossil fuel plants and 23˚F for nuclear plants (Electric Power Research Institute, 2004). This heated water is discharged back to the environment in once-through cooling systems, or is cooled and then re-used in recirculating cooling systems.

Cooling systems can impact environmental quality in natural bodies of water through the withdrawal of water, the discharge of heated water and the net consumption of water. Aquatic organisms may be killed through *impingement*, the trapping of organisms against intake structures or through *entrainment*, the intake of these organisms into cooling systems that are then killed as a result of exposure to chemicals, heat, pressure or mechanical impact. *Thermal pollution* can result from the discharge of water that is significantly warmer than the receiving body of water. Net consumption may lower water levels or reduce stream flows, impacting local ecosystems. The overall environmental impact of a cooling system is directly related to the quantity of water used by that system. Given the simultaneous increases in world power demand and water scarcity, the development of water conserving cooling technologies will be extremely important. (Rosenberg, 2013)

[1] The exception is plants fired by natural gas, which usually use the gas combustion to spin turbines directly without the production of steam.

The environmental impacts of withdrawals by cooling systems are well documented. The first set of impacts are caused by cooling water withdrawals. As stated by the EPA (2012), "The withdrawal of cooling water by facilities removes billions of aquatic organisms from waters of the United States each year, including fish, fish larvae and eggs, crustaceans, shellfish, sea turtles, marine mammals, and other aquatic life." Most of these impacts are to early life stages of fish and shellfish. The scale of this problem is suggested by a 2011 proposed rule on intake structures that would cover, "… roughly 1,260 existing facilities that each withdraw at least 2 million gallons per day of cooling water." (U.S. EPA, 2011)

The second set of potential impacts are caused by the discharge of water at significantly increased temperatures, which has the potential to impact aquatic life in the affected bodies of water either directly or through temperature-related effects on the water's capacity to absorb dissolved oxygen. Research has suggested that thermal emissions can have a significant impact on general water quality. (Verones et. al. , 2010) Because water temperature plays an important role in regulating metabolic and growth rates as well as reproduction, changes in water temperature can disrupt normal biological process and potentially lead to death of aquatic organisms. (Arieli et. al. 2011; Sylvester 1972; Dembski et. al. 2006) Thermal emissions may impact routes and destinations of migratory fish (Yadrenkina 2010 and Wither et. al. 2012) or lead to displacement of native species by more thermally tolerant species. (Leuven et. al. 2007). In addition to direct effects on aquatic ecosystems, thermal pollution can have indirect effects through its contributions to *eutrophication*, or diminished oxygen levels, both because warming reduces water's ability to hold dissolved oxygen and because warmer water promotes algae blooms whose decomposition consumes vast amounts of oxygen, leaving only species that can tolerate low oxygen levels.

The third set of impacts results from net consumption changing water levels or stream flows. Changes in stream flows can have a variety of ecological impacts, ranging from changes in the mobility of bottom-dwelling organisms (Minshall and Winger, 1968) to impacts on the balance between native and non-native species (Marchetti and Moyle, 2001). Poff and Allen (1995) go so far as to suggest that anthropogenic disturbances that impact stream flow could significantly increase the abundance of generalist fish species at the expense of specialist species.

*Policy Background*

The impact of cooling systems on natural bodies of water is perpetually a topic of policy interest and an issue for which the EPA has recently set rules. There has been a long legal struggle surrounding rules for intake structures. Failure to finalize an initial set of rules for equipment to reduce impingement and entrainment lead to a 2009 decision by the U.S. Supreme Court in the *Entergy v. Riverkeeper* case that required the EPA to reconsider the rules they had issued.

As a result of the controversy surrounding the enforcement of the CWA, it is important to understand how regulation has impacted the operation of water cooling systems. Prior to implementation of the CWA, cooling systems were largely unregulated and there was little or no incentive on the part of manufacturers of once-through cooling systems (the main technology at the time) to mitigate any detrimental impacts. The CWA effectively put pressure on once-through systems, forcing utilities that wanted to install once-through cooling systems to design and operate them so as to provide the necessary cooling without affecting local aquatic ecosystems[2]. This sort of pressure might spur technological advance in an otherwise static industry.[3]

Modern efforts at water pollution control in the U.S. are set in the 1972 CWA, which was further amended in 1977. The requirements of the CWA tend to be dependent on what is technologically achievable, and this technology-based aspect of the regulation is embodied in Section 301 of the CWA, which states, "… there shall be achieved not later than July 1, 1977, effluent limitations for point sources… which shall require the application of the best practicable control technology currently available as defined by the Administrator…"

The Clean Water Act directly addresses the issues of water intake and thermal pollution. In discussing water intake structures, Section 316(b) specifies, "...that the location, design, construction, and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact," but doesn't explicitly state that reduced intake might be a substitute for more effective technology.[4] In discussing thermal emissions, Section 316(a) specifies that limits on thermal emissions, "…will assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on that body of water." Presumably this inherently considers the volume as well as thermal content of any discharges. Consistent with Section 301 of the CWA, the best practicable control technology is to be used to control thermal emissions. The best practicable technology for reduction of thermal emissions is recirculating or closed-cycle cooling systems, but the CWA also allowed for exceptions. Section 316 of the CWA states, "…any point source of a discharge having a thermal component… which, as modified, meets effluent limitations … and which effluent limitations will assure protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in or on the water into which the discharge is made, shall not be subject to any more stringent

[2] While simple, relatively inexpensive mechanisms exist to reduce the environmental impacts related to cooling water systems in general, they are not sufficient to protect waterways to the extent that the CWA prescribes. Travelling screens, which lift aquatic organisms as well as debris out of intake streams, have been employed at some locations to reduce impingement and entrainment and researchers such as Black (2007) have worked to improve their effectiveness. Thermal diffusers are used to mitigate the thermal pollution impacts of warm water discharges (Roberts, 2011).

[3] There has been research into development of water-saving cooling technologies, as suggested by at least one article in Power Engineering from August of 2012.

[4] However, the decision of the Supreme Court in the *Riverkeeper v. Entergy* case suggests that this requirement may be subject to some sort of balancing of benefits and costs.

effluent limitation with respect to the thermal component of its discharge…" This phrasing has been interpreted as meaning that a facility may install and operate a once-through cooling system if it can demonstrate that the discharges will not be detrimental to a balanced, indigenous population in the affected bodies of water. In addition to the exceptions specifically listed in the CWA, plants in existence before the CWA became law had flexibility in their choice of water cooling systems given the EPA's inability to promulgate a rule on water cooling technology.[5]

The impact of the form of environmental policy on the rate of technological advancement in the regulated industry has received wide attention in the academic literature. Several theoretical papers (Zerbe (1970); Wenders (1975); Requate and Unold (2003)) find that technological standards generally offer incentives for innovation that are smaller than those offered by market-based regulations. Alternatively, David and Sinclair-Desgagne (2005) argue that a monopolistic supplier of pollution control equipment regulated with a technology standard will provide strong incentives for technological advancement as the monopolist can capture all of the rents from the polluting firm.

There has been extensive work examining the relationship between environmental regulation and environmental innovations.[6] A majority of the empirical analyses of this relationship comes from the electric power industry. Popp (2003), Lange and Bellas (2005), Keohane (2006), and Perino (2011) test the impact of the change in sulfur dioxide regulation from an emissions standard to a tradable permit scheme. These papers generally find results consistent with the theoretical literature that emissions standards do not provide strong incentives for technological advancement. Taylor et. al. (2003) is an exception. Bellas and Lange (2010) find evidence in support of the David and Sinclair-Desgagne (2005) hypothesis, where technological advance will occur but be captured by the supplier for particulate matter control equipment. This analysis will provide further insight into the relationship between technological advancement and environmental regulation.

## IV. Model

To determine whether technological advancement has taken place, we estimate performance-adjusted hedonic models for rate of water withdrawals and thermal emissions using two versions of our data. We first estimate the models using data from the year 2004. The dependent variables do not change very much over time so estimating one year gives similar results to estimating a panel model, however the panel model is more difficult to estimate when controlling for the potential selection bias of type of cooling system. While we present results from 2004, the

[5] The technological basis for the standard set by the EPA was reinforced in the U.S. Supreme Court's decision which states that the EPA's rules for new, large cooling water system require them to, "…restrict their inflow 'to a level commensurate with that which can be attained by a closed cycle recirculating cooling water system.'

[6] An excellent review of the theoretical and empirical research in this area is provided by Popp et. al. (2010).

models have been run for each of the years between 1996 and 2005 with the same sign and significance of the explanatory variables. An additional sample is run using average values of the dependent variables over the time period 1996-2005 and estimates the model given below on these average values.

Explanatory variables in the analysis are the year the cooling system came online (inservice year, a proxy for the cooling system vintage), the type of cooling system (once-through or recirculating), whether the cooling system was installed after the CWA was passed, an interaction of the inservice year and the CWA variables, total annual generation and the square of total annual generation (generation capacity and capacity squared is used when the average dependent variable is utilized).[7]

As discussed above, cooling system type is endogenous. Especially after the CWA was passed, plants could only utilize a once-through system if it could be shown that this system did no more environmental damage than a recirculating system. It is expected that once-through systems that were actually installed will have smaller impacts on intake rates and thermal discharges when the potential selection bias is not controlled for compared to when this bias is taken into account. To control for the potential selection bias, an instrumental variable estimation is run (Angrist et.al., 1996). Here, the choice of cooling system type is first estimated using explanatory variables (instruments) that affect the choice of cooling system type but not the level of water withdrawals or thermal pollution. The predicted cooling system type is then used in a second stage estimation. Two instruments are used to predict cooling system type. The first is whether the plant takes its water from a natural source (river, lake, or ocean, indicated by the dummy variable *natural*) as opposed to a well or municipal source. The natural dummy reflects the fact that allowances for thermal impacts might be greater for cooling systems withdrawing from and discharging to artificial rather than for natural bodies of water. The second instrument is whether the water source utilized by the plant was listed as an impaired body of water by the EPA in 2004. While all of the cooling system type decisions were made prior to 2004, the impaired listing implies that other polluting sources are using this water source, reducing the probability that a once-through system could show it would not have a greater environmental impact then a recirculating system.

Formally, the estimating model is:

$$Y_i = \alpha \hat{T}_i + \beta I_i + \gamma CWA_i + \delta CWA_i * I_i + \varphi G_i + \varepsilon_i$$

where

$Y_i$ is either the log of the rate of water withdrawals or thermal pollution for unit *i*

$\hat{T}_i$ is the predicted cooling system type for unit *i*

[7] Using a quadratic function of generation allows for the possibility of economies of scale in cooling.

$I_i$ is the inservice year of the cooling system for unit $i$

$CWA_i$ indicates whether unit $i$ was inservice after the CWA was passed

$G_i$ are generation variables for unit $i$

The coefficient on $I_i$, $\beta$, will reveal the pace of technological change in reducing the environmental impacts of cooling systems before the CWA altered firm's decisions related to cooling system type. The coefficient on the interaction of $CWA_i$ and $I_i$, $\varphi$, will reveal how this pace was altered by passage of the CWA.

Data for the analysis are taken from the U.S. Energy Information Administration's Form EIA-767 from the years 1996 through 2005. The EIA-767 includes information about the design and operation of thermal generating plants in the United States. The level of the observation is the cooling unit and the generator with which the cooling unit is matched. Often there is one cooling unit-generator match per plant but not always.

The first dependent variable, the *Rate of Withdrawl*, is the average annual rate of withdrawal in cubic feet per second. The second dependent variable, the *Rate of Thermal Pollution*, is the product of the annual average rate of discharge in cubic feet per second and the difference between the intake temperature and the outflow temperature.

*Inservice Year* is the year in which the cooling unit came into service, and serves as an indicator of the vintage of the cooling unit. *CWA* is a dummy variable indicating whether the cooling unit is subject to regulation under the CWA as a new unit, depending on whether it came on line after the passage of the CWA. *Total Generation* is the total amount of electricity generated at the associated generator(s) during the year, in terrawatthours. *Generation Squared* is the squared value of *Total Generation* and allows for the possibility of economies of scale in generation and cooling.[8]

*Natural* is a dummy variable indicating whether the water source associated with the cooling system is natural: a lake, river or ocean. *Impaired water* is a dummy variable that is equal to one if the water body that the plant utilizes, within a radius of 1 Km, is listed as impaired by the EPA and is zero otherwise. The impaired water data were extracted from the EPA Impaired Waters and Total Maximum Daily Loads dataset of the Clean Water Act 303(d) for 2004 with the use of ArcGIS. This dataset lists water bodies that are highly polluted or are otherwise too degraded to meet US water quality standards. However, the dataset does not include all impaired waters state by state; instead it includes the waters that comprise a state's approved CWA 303(d) list. Unfortunately, this list is updated irregularly and at the discretion of the individual states, so annual changes in impaired status are not accurately reflected.

[8] *Maximum Generator Capacity*, the sum of the maximum generator nameplate ratings, in megawatts, of the generators associated with the cooling unit and its squared term is used when using the dependent variables are their average values over the period 1996-2005.

Summary statistics are given in Table 1. Cooling water withdrawals and thermal pollution discharges are much greater for once-through cooling units than for recirculating units. Once-through units represent 61.5% of the units in the set, but only 21% of the post-CWA units. Both recirculating and post-CWA units (which have a great degree of overlap) tend to be larger than once-through and pre-CWA units, as indicated by both the generator capacity.

**Table 1: Summary Statistics, Means and Standard Deviations**

| Sample | All | Once Through | Recirculating | Pre-CWA | Post-CWA |
|---|---|---|---|---|---|
| Variable | Mean (S.D.) | Mean (S.D.) | Mean (S.D.) | Mean (S.D.) | Mean (S.D.) |
| Rate of Water Withdrawl ($ft^3$/sec) | 203.57 (291.61 | 299.11 (311.35) | 61.01 (183.91) | 210.79 (295.85) | 147.49 (258.73) |
| Volume of Thermal Pollution (degrees F $ft^3$/sec) | 4804.78 (5661.37) | 5743.23 (5600.65) | 1767.28 (4753.61) | 4924.25 (5790.44) | 5293.11 (6746.42) |
| Once Through System | 0.61 (0.48) | 1 | 0 | 0.73 (0.44) | 0.21 (0.41) |
| Inservice Year | 1965 (12.25) | 1961 (9.65) | 1971 (12.96) | 1960 (8.94) | 1980 (5.17) |
| After Clean Water Act | 0.23 (0.43) | 0.08 (0.27) | 0.46 (0.49) | 0 | 1 |
| Generator Capacity | 0.38 (0.34) | 0.34 (0.31) | 0.45 (0.38) | 0.31 (0.32) | 0.58 (0.31) |
| Natural Water Body | 0.87 (0.33) | 0.99 (0.10) | 0.68 (0.46) | 0.89 (0.31) | 0.79 (0.41) |
| Impaired Water | 0.37 (0.48) | 0.43 (0.49) | 0.26 (0.44) | 0.42 (0.49) | 0.21 (0.40) |

## V. Results

Water withdrawal model results are given in Table 2. The first two columns utilize only data from the year 2004 while the third and fourth column use the average water withdrawal over the 1996-2005 sample. Results are consistent across the two models and samples. The first and third column show the results without correcting for the potential selection bias in type of cooling system while the second and fourth column employ an instrumental variables technique to correct this selection bias. The results reveal that the "naïve" estimation would underestimate the effect of a once-through system on water withdrawals, as the instrumented coefficient on once-through systems is larger. This is expected given that the CWA allows plants to install once-through systems if they can show that they will not impact the environment more than recirculating systems. All of the tests of instrument validity (F of excluded instruments, Underidentification, and Overidentificaiton) pass their respective null hypothesis to be considered valid instruments. There are clearly economies of scale in withdrawal as the generation variable is positive while the generation squared variable is negative, implying that a doubling of generation requires less than twice the amount of water.

**Table 2: Water Withdrawal Results**

| Model | OLS | IV-GMM | OLS | IV-GMM |
|---|---|---|---|---|
| Sample | 2004 | 2004 | Average All Years | Average All Years |
| Variable | Coefficient (S.E.) | Coefficient (S.E.) | Coefficient (S.E.) | Coefficient (S.E.) |
| Once Through System | 3.10*** (0.08) | 4.10*** (0.17) | 2.98*** (0.09) | 3.64*** (0.16) |
| Inservice Year | 0.01*** (0.004) | 0.02*** (0.005) | 0.01** (0.004) | 0.01*** (0.006) |
| After Clean Water Act | 0.09 (0.16) | 0.35** (0.18) | 0.35** (0.16) | 0.59*** (0.17) |
| Inservice Year/After Clean Water Act Interaction | -0.03 *** (0.01) | -0.02* (0.01) | -0.05*** (0.02) | -0.05*** (0.01) |
| Generator Capacity | 3.74*** (0.50) | 3.34*** (0.51) | 3.47*** (0.41) | 3.25*** (0.43) |
| Generator Capacity Squared | -1.31** (0.38) | -1.02*** (0.38) | -0.98*** (0.33) | -0.82** (0.31) |
| N | 1016 | 1015 | 1226 | 1226 |
| F-test of excluded instruments | | 168.44 | | 203.55 |
| Underid P-value | | 0 | | 0 |
| Overid P-value | | 0.83 | | 0.26 |

Notes: *, **, *** correspond to 10, 5, and 1% statistical significance respectively. Standard errors clustered at the plant level. The first two columns use data from 2004. The third and fourth column uses the average values from 1996-2005. The dependent variable is the log of the rate of water withdrawl.

The pattern of technological change revealed in Table 2 suggests that systems were using water more intensively until the passage of the CWA, after which the trend reversed. Adjusting for performance, newer vintage cooling systems withdrew about 1% more water than the previous year's cooling system until 1973 when newer systems started withdrawing between 2 and 4% less water for each vintage year.[9]

Turning to the rate of technological progress for thermal pollution, Table 3 provides the results from these estimations. As in Table 2, Table 3 provides estimates from one year of the sample

[9] Given that the inservice year and inservice year CWA interaction are dummy variables, one can't interpret their coefficients as percentage changes (Halvorsen and Palmquist, 1980) with transforming the coefficients.The rate of progress after 1973 is found by adding the coefficient on inservice year and the interaction of inservice year and the CWA dummy.

(columns 1 and 2) and an average across all years (column 3 and 4). The odd numbered columns are the OLS results while the even numbered columns provide the instrumental variable results. The estimates provide a similar story to those from the water withdrawal. Again, the naïve estimation would under report the impact of once-through cooling systems on thermal pollution as evidenced by the OLS results compared to the instrumental variable results. The tests of instrument validity confirm that the instruments are valid. Also similar to the withdrawal results, there are diseconomies of scale in thermal pollution as the linear generation term is positive and the squared term is negative.

**Table 3: Thermal Pollution Results**

| Model | OLS | IV-GMM | OLS | IV-GMM |
|---|---|---|---|---|
| Sample | 2004 | 2004 | Average All Years | Average All Years |
| Variable | Coefficient (S.E.) | Coefficient (S.E.) | Coefficient (S.E.) | Coefficient (S.E.) |
| Once Through System | 3.98*** (0.20) | 5.24*** (0.39) | 4.12*** (0.15) | 6.39*** (0.35) |
| Inservice Year | 0.02*** (0.005) | 0.03*** (0.007) | 0.02*** (0.005) | 0.03*** (0.006) |
| After Clean Water Act | 0.30 (0.29) | 0.43 (0.30) | 0.27 (0.26) | 0.61* (0.32) |
| Inservice Year/After Clean Water Act Interaction | -0.09*** (0.03) | -0.07** (0.02) | -0.10*** (0.02) | -0.10*** (0.03) |
| Generator Capacity | 2.85*** (0.56) | 2.57*** (0.57) | 3.94*** (0.45) | 3.76*** (0.48) |
| Generator Capacity Squared | -0.75** (0.35) | -0.55 (0.40) | -1.08** (0.33) | -0.92** (0.35) |
| N | 687 | 687 | 1059 | 965 |
| F-test of excluded instruments | | 44.27 | | 76.81 |
| Underid P-value | | 0.00 | | 0.00 |
| Overid P-value | | 0.11 | | 0.11 |

Notes: *, **, *** correspond to 10, 5, and 1% statistical significance respectively. Standard errors clustered at the plant level. The first two columns use data from 2004. The third and fourth column uses the average values from 1996-2005. The dependent variable is the natural log of the rate of volume of thermal pollution.

The pattern of technological change is similar to that for water withdrawals. Initially, cooling systems were emitting 3% more thermal pollution from one year's vintage to the next. Since the CWA came into effect, cooling systems are emitting between 4 and 8% less thermal pollution from one vintage year to the next.

Given the thermal properties of a steam electric generation system, it is not surprising that the results across the two models reveal a similar story. The surprising result is that these systems had a technological advance after imposition of the technology standard in the CWA. As referenced above, most theoretical and empirical evidence points to technological standards as providing little incentive for advancement. A more detailed investigation of the cooling water systems industry may help reveal what made it bring technological advances to the market while other pollution abatement technologies, generally those also for use at power plants, stagnate.

## VII. Conclusion

Cooling systems are a necessary component of most thermal generating plants, but their water withdrawals and thermal pollution discharges can have important environmental impacts. The CWA addresses these issues through technology standards that essentially establish recirculating cooling systems as a favoured technology, leaving once-through systems as a secondary option only available where it will not have impacts beyond those of a recirculating system. A long line of analyses, both theoretical and empirical, have shown that technology standards provide little incentive for technological advancement to. We examine the impact of the CWA on the rate of technological advance by analysing changes in the performance-adjusted rates of cooling water withdrawals and thermal pollution emissions. Our results suggest that cooling water systems have brought technological improvements to the market since the CWA was enacted. Newer cooling systems introduced since the CWA use significantly less water and discharge less thermal pollution. This result persists even after controlling for the possible selection bias in technology choice that occurred due to the possibility of using once-through systems if a plant can show its environmental impacts are not above that of the technology standard.

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