Mitigation of electricity production externalities imposed on water resources and fishing industries in the Delaware River estuary and implications for offshore wind energy policy

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Abstract

One often-overlooked benefit of wind energy is improvement in aquatic ecosystem health. Operation of wind turbines uses no water whereas conventional energy requires water for cooling. In this case study, we calculate the withdrawal externalities in the lower Delaware River estuary. We focused on power plants with once-through cooling water intake systems. Combined, these plants on average circulate a volume equal to 34% of the discharge of the river system. After use, most water is discharged into the river, reducing water quality because it has a high temperature, low dissolved oxygen, and contains biocides. While plants are withdrawing water, fish are caught in the water flow and are impinged against screens or entrained within the system, causing them to die and impacting fishing industries. In the Eastern US, power plants claim a right to withdraw water freely; however, this right is void if the withdrawals are unreasonable, affecting water quality and availability. We argue these withdrawals are unreasonable because alternatives exist (recirculating cooling water intake systems) that greatly reduce externalities and water withdrawn by these power plants is disproportionate compared to the amount of frontage they occupy along the Delaware River. Furthermore, water rights are subject to review and reallocation, no matter how long held. If assigned the proxy value of non-potable water, water externalities at a natural gas plant are \$0.041/kWh, and losses to weakfish, Atlantic croaker, striped bass, alewife, blueback herring, and blue crab fisheries are \$0.001/kWh. If other water externalities (water quality, consumption of water, impact to ecosystems) were monetized, the combined cost would be higher. Retrofitting a natural gas plant to use recirculating cooling water intake systems costs \$0.014/kWh (including costs of water externalities that remain) and reduces 96% of withdrawals. Thus, retrofitting is a cost-effective mitigation technology today. In the future, if new generation is to be built, a likely option is natural gas combined cycle plant with carbon capture sequestration technology. However, the cost differential between this energy source and offshore wind energy is \$0.027/kWh, which costs less than water externalities, making offshore wind energy a cost effective mitigation technique for future energy development. To account for externalities, states can charge power plants for water, tax for fish deaths, require use of recirculating systems, or incentivize offshore wind energy. We demonstrate that pricing water withdrawals and accounting for externalities have significant influence on the energy market.

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[1] When this analytical paper is submitted for publication, Lance Noel will be a co-author of the manuscript. Lance Noel assisted in determining the geographic scope and designing the methodology for the analysis. He contributed to data collection of historical water usage, electricity production, and impingement and entrainment of power plants in the Delaware River estuary, and assisted on the legal implications.

1. Introduction

Coal, natural gas, and nuclear fuel are the conventional sources of electricity generation in the U.S. The price that consumers pay does not represent its true cost. The market price does not include all costs of generation: human health effects, climate change, ocean acidification, and other environmental degradation. These costs are called externalities because they are external to the market price yet cause real costs to society (European Commission, 2003; NEEDS, 2009; NRC, 2010; Muller et al., 2011; Epstein et al., 2011). Epstein et al. determined that the true social cost of coal is on average 17.8¢$_{2008}$/kilowatthour (kWh) (2011). If this cost were added to the typical market price for electricity in the Mid-Atlantic (EIA, 2013c), the market price would nearly triple.

These studies predominantly include human health risks and climate change and have not included costs of externalities caused by water use. This analysis evaluates the costs of water externalities caused by electricity production that have been absent in the literature. Water externalities result from use of power plant cooling water intake structures (CWIS). As a case study, this analysis focuses on power production within the lower Delaware River estuary, an area that is tidally influenced and supports several estuarine fish species. Because we focus on a finite region, this analysis is a conservative estimate of the externalities impacting the entire system of the Delaware River.

Within the Eastern US, nearly half of generation is produced with plants with once-through CWIS that withdraw water continuously from natural water bodies or water reservoirs and return used water of considerably lower quality (Averyt et al., 2011). In contrast, recirculating CWIS reuse water until entirely evaporated. With any CWIS, water that evaporates is not returned to the ecosystem and classified as consumed. Though recirculating CWIS withdraw less water, they consume more water than once-through CWIS. Power plants that have once-through CWIS are the focus of this analysis because they contribute to most water withdrawals within the region. Nationwide, power plants withdraw more water than any other sector, including mining, irrigation, industry and public supply combined, and in 2005 constituted 49% of withdrawals (Kenney, 2009).

Water withdrawals impact the environment, and these damages are defined as externalities because they cause economic consequences. The Delaware River provides many ecosystem services that benefit the region’s economy (Kauffman et al., 2011). Externalities interfere with ecosystem services. Water withdrawals disturb ecosystems by disrupting river flow, drawing in fish and shellfish, and discharging used water with a higher temperature and low dissolved oxygen content. The phenomenon affecting fish is described as impingement and entrainment (I&E). Impingement is entrapment of organisms against screens in the intake system and typically affects juveniles and young adults, causing fatal injury. Entrainment happens when small organisms like larvae and eggs pass through the screens and are caught and killed in the CWIS. The resultant loss has economic consequences for commercial and recreational fisheries.

Damages are also caused when water is returned after use in CWIS. Returned water has higher temperatures, causing low dissolved oxygen levels. It also often contains biocides that have been added to prevent accumulation of biological material within the CWIS. The volume of returned water can constitute a large portion of a natural water body. Within our study region, power plants circulate and discharge a volume of water that is on average 34% of the combined mean annual discharge of the river system, meaning that about a third of the water flowing past this region will have overall reduced quality (see Technical Appendix A). Facilities including treated municipal wastewater, industrial, and power plants also discharge into the region, so the power plants circulate water that is already of reduced quality in addition to freshwater. As a result, the power plants further reduce the quality of the river.

Within the Delaware River Basin and throughout much of the Eastern regions of the US, power plants do not pay for water withdrawals because plants claim a riparian right to use water as landowners along the river shoreline. Riparian rights are governed by the states and require that water use must be reasonable (Restatement (Second) of Torts §850A, 1979; Cox, 2008). Reasonable use depends on the context of the cumulative water use within the region. Water use cannot unnecessarily affect the availability and quality of water for other riparian users, including society. In addition to the multiple industries and power providers along the river that use water, the public also are riparian users, and the public have an interest in utilizing riparian ecosystems for recreation. Unreasonable water use can detriment these ecosystems for public use, especially commercial and recreational fishermen.

Within the Delaware River Basin, the availability of water for riparian users is ensured by the Delaware River Basin Commission (DRBC), a regional compact of neighboring states. The DRBC charges facilities along the Delaware River and nearby tributaries to contribute to operation and maintenance of water supply storage in federally-owned reservoirs (DRBC, 2014). Facilities include industry, electricity, public water supply, irrigation, and ski and golf recreational facilities (DRBC, 2012a) and are charged for water that is withdrawn and consumed. Rates change with distance of the facility's location from the reservoirs (DRBC, 2010). Facilities at farther distances, including those in our analysis, pay a discounted rate (DRBC, 2010, Technical Appendix H). Revenues generally cover 11% to 31% of the costs of the reservoirs (DRBC, 2013b), so the entire cost of ensuring availability is not captured in the DRBC charging program. Though there is no shortage of water currently, demand for water will likely grow, and availability could become problematic. Some areas in the Mid-Atlantic, especially Delaware, are expected to experience water sustainability issues due to climate change effects in the future (NRDC, 2010). Additionally, these charges do not compensate for externalities caused by water withdrawals.[2] In effect, power plants only partially cover the costs of water availability and do not compensate for reduced water quality that directly affects other riparian users.

Water use by riparian owners must be reasonable, ensuring availability and quality of water. In this analysis, the power plants have water withdrawals that are unreasonable for three main reasons. One is that recirculating systems are viable alternatives that exist and would substantially reduce withdrawals and ensuing externalities while still producing electricity at the existing plants. Recirculating systems reduce withdrawals by 93 to 98% (EPRI, 2011) and I&E by similar proportions. A second reason is that the portion of water withdrawn by these power plants is

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[2] The DRBC addresses some water externalities because they regulate water quality. However, the DRBC acknowledges that water quality of this region is of concern because some areas are still not classified as "fishable" or "swimmable," and attaining these statuses is a stated goal of the Clean Water Act (CWA) (DRBC, 2012b).

disproportionate compared to the amount of frontage these power plants have along the Delaware River (see Technical Appendix A). A final reason is that these withdrawals cause damages that under the public trust doctrine, water rights are subject to review and reallocation, no matter how long held (discussed in Section 4.5). Even though power plants have been operating in these ways for decades, their practices are subject to review, regardless of whether alternatives (recirculating CWIS) exist. Because we argue the water withdrawals are unreasonable, we consider water withdrawals as externalities. The state does not charge for the use of the water or ensuing externalities, and in effect, free water withdrawals are subsidies for power production given by the state.

We illustrate this subsidy by assigning the water withdrawals a price and use the market value of industrial, non-potable water as a proxy. Industries (including other conventional power plants in the region) that do not claim a riparian right to withdraw water pay for industrial, non-potable water. Power plants would also pay for this water if they could not claim a riparian right, such as their riparian right is void because their water use is unreasonable.[3] This proxy value is not the true social value of water or the true value of the externality of reduced water quality. There have been attempts to charge for water externalities in the Australian water sector (Frontier Economics, 2011), but charging for water externalities caused electricity generation has not been done. The true cost of water externalities would be the cost of mitigating all the effects of the externalities: compensation for disruption of ecosystems, consumed water, reduced quality of returned water, and unnecessary pressure on water managers. Likewise, defining a price that matches the social value of water itself is difficult, as it is not usually reflected in market values (van der Zaag and Savenije, 2006). In the absence of data evaluating the true social value of water or the costs of water externalities, we choose to use the proxy value.

We also demonstrate economic losses associated with I&E of fish stocks that are fished by commercial and recreational fishermen. Though selectively monitored by the Environmental Protection Agency (EPA), I&E is an externality that requires better understanding. Section §316(b) of the Clean Water Act (CWA), 33 USC 1326, requires CWIS be designed to minimize adverse environmental impact, including I&E. I&E studies are typically plant-specific and of limited duration because they are only required during occasional permit renewal when the EPA determines a plant has adverse environmental impact. As such, it is difficult to determine impact to local populations. Furthermore, implementation of Section §316(b) has been a contentious and difficult problem (*Cronin* v. *Browner* 898 F. Supp. 1052 1995; *Riverkeeper* v. *EPA* 475 F.3d 83 2007; Odom, 2010). Despite this, it is clear from studies used in our analysis that fisheries lose potential harvest and revenue due to I&E. The EPA has estimated losses to fisheries on a regional basis such as the Mid-Atlantic (EPA, 2006; EPA, 2011). In this analysis, we estimate economic impacts to fisheries specifically from plants in the lower

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[3] If power plants could not claim a riparian right and thus could not pump water themselves, they would need to buy water from a supplier. This proxy value is the price they would pay to a supplier. If power plants could claim a right to pump water but the right did not include free use of the water, they would likely pay the state for water. In this case, they would pay a percentage of the proxy price that excludes the costs of pumping the water, treating it, and transporting it. This percentage is the cost of the water company's plant assets (including access to water) and rate of return (see Technical Appendix E).

Delaware River, including one not included in the EPA cost assessment (EPA, 2006; EPA, 2011).

For comparison purposes, we demonstrate the costs of retrofitting to recirculating CWIS and employing offshore wind energy as alternatives to the current practice of once-through CWIS. We use offshore wind energy because it is the largest available renewable resource close to the same load centers as served by the existing thermoelectric power plants affecting the Delaware River (EIA, 2014). Offshore wind power uses negligible water during operation (Keith et al., 2012; Macknick et al., 2012) and thus causes no water externalities typically caused by conventional generation. We compare the costs of these mitigation technologies to the costs of externalities per unit of energy produced (kWh).

Offshore wind energy developments in the U.S. have not yet been built and are currently in the planning and permitting stages. Once constructed and commissioned, these initial developments are expected to be more costly than current electricity generation in the Mid-Atlantic (EIA, 2013), as demonstrated by the 468 MW Cape Wind project in Massachusetts that will cost 18.7¢$_{2012}$/kWh (DPU, 2012). This price difference is due to high capital investment costs for offshore wind projects associated with risk, development of infrastructure, and turbine foundations (Musial and Ram, 2010; Levitt, 2011; NREL, 2012; Wiser and Bolinger, 2013). Including externalities caused by conventional energy into cost assessments may demonstrate that the price of offshore wind energy is competitive with conventional energy.

Though the U.S. offshore wind energy industry is in its infancy, land-based wind energy is a fast-growing renewable energy technology and has dramatically increased over the past decade from 1 gigawatt (GW) of cumulative capacity in 2002 to 60 GW in 2012 (Wiser and Bolinger, 2013). Although land-based wind energy has at times in the past encountered high turbine costs (Bolinger and Wiser, 2009; Bolinger and Wiser, 2012) and currently faces some financial uncertainty (Baradalle, 2010), wind energy is now competitive in the energy market (Lazard, 2013). State renewable portfolio standards, the federal production tax credit, and state-level incentives and policies helped contribute to this rapid development (Bird et al., 2005; Menz and Vachon, 2006; Wiser et al., 2007; Carley, 2009).

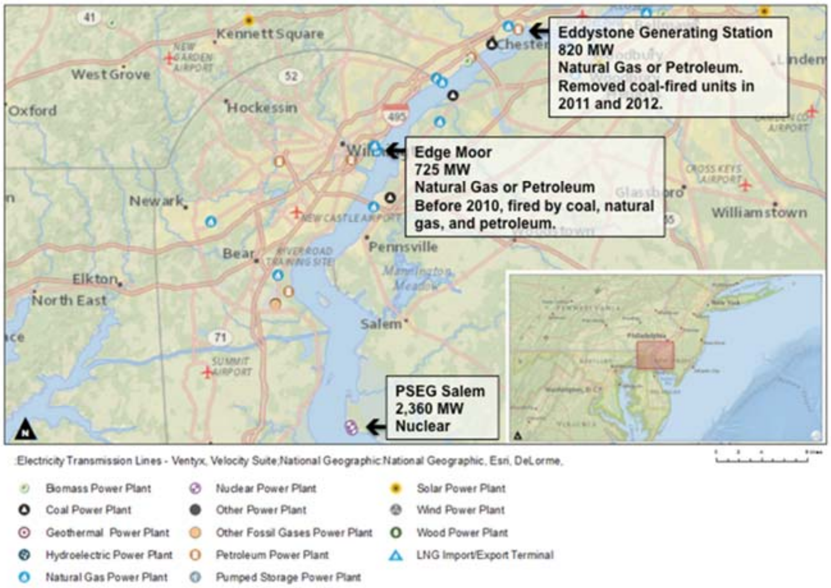
Such policies supporting wind energy development are reasonable financial strategies as they are akin to long-term and continued subsidies for coal, natural gas, petroleum, and nuclear industries (Environmental Law Institute, 2009). Moreover, considering the entirety of the externalities associated with conventional energy fuel mining, transportation, generation, and disposal, the case for financial incentives for wind energy development is even more compelling. New policies that account for externalities could be created so that wind energy can compete fairly with the true cost of conventional energy sources. Policies such as taxes for damages would effectively reward wind energy for the harms it avoids, further incentivizing wind development. Furthermore, analysis and recognition of these externalities at a bare minimum justify financial incentives for wind energy as established by federal and state policies.

2. Methodology

2.1. Geographic scope

We focused on the lower Delaware River estuary (Figure 1) as a way to bound the analysis. In this stretch, the River supports species adapted to an estuarine environment compared to upper reaches of the river that support more freshwater species (personal communication with Dr. D. Kahn, Delaware Department of Natural Resources and Environmental Control (DNREC), on January 11, 2013). Commercially fished species are more abundant within our geographic scope compared to upriver where species are fished recreationally. Biological monitoring studies also reveal a different range of species (see Technical Appendix B).

Several plants in the region withdraw water from the Delaware River (see Technical Appendix C). Salem, Edge Moor, and Eddystone consistently withdrew the most water. Combined, they constitute between 96% and 98% of the water withdrawn in years 2001-2011. We focus our analysis on these three plants because they represent the almost the entirety of the water withdrawn.



Eddystone Generating Station
820 MW
Natural Gas or Petroleum.
Removed coal-fired units in 2011 and 2012.

Edge Moor
725 MW
Natural Gas or Petroleum
Before 2010, fired by coal, natural gas, and petroleum.

PSEG Salem
2,360 MW
Nuclear

Electricity Transmission Lines - Ventyx, Velocity Suite;National Geographic;National Geographic, Esri, DeLorme,

http://www.eia.gov/state/

Figure 1. Geographic scope of the analysis: lower Delaware River estuary, south of Philadelphia, PA and north of Middletown, DE. Large capacity power plants studied are identified. Text is overlaid maps produced by the Energy Information Association.

2.2. Calculation of externalities

We represent externalities as a unit of damage per kWh of electricity produced (e.g., gallons/kWh, fish/kWh). Considering external costs on a per-kWh basis allows for an equal comparison between conventional energy and offshore wind energy based on the good society demands — electricity. Historical electricity production data was obtained from the Energy Information Association (EIA) Form EIA-923. We monetize impacts based on values in Table 1.

Table 1. Monetary values used in calculations of externalities. Values were translated into 2013 dollars using the Consumer Price Index.

Variable in Externality Calculation	**Assigned Monetary Value**
*Water withdrawn (total payments to supplier)**	$2.3659/thousand gallons
Water withdrawn (costs of water supply)▯	$0.2602/thousand gallons
Market Value of Commercial Landings in Delaware, Maryland, and New Jersey+	
Weakfish	$1.47/pound
Atlantic croaker	$0.57/pound
Striped bass	$2.31/pound
Alewife	$0.42/pound
Blueback herring	$0.52/pound
Blue crab	$0.48/pound
Revealed Preference for Enhanced Recreational Catch in Delaware, Maryland, and New Jersey±	
Weakfish	$4.78 per one extra fish caught
Atlantic croaker	$4.78 per one extra fish caught
Striped bass	$4.78 per one extra fish caught
Alewife	No data available
Blueback herring	No data available
Blue crab	No data available

* Prices are rates of local water supply company United Water (United Water, 2011). The first 1.4 million gallons withdrawn a month are $3.1697/thousand gallons. Subsequent withdrawals are $2.3659/thousand gallons. Most water is valued at $2.3659/thousand gallons because the first 1.4 million gallons are less than 0.02% of the water withdrawn monthly.

▯ Costs of the water supply are 11% of the rates charged by local water supplies like United Water.

\+ Average commercial landings price from years 2002 to 2012 (ACCSP, 2013).

± Revealed preference of a recreational fisher's value of enhanced harvest for a recreational fishing trip for one extra fish, based on state-specific values and fish size categories (Hicks et al., 1999).

2.2.1. Water withdrawal and consumption externalities

We obtained gallons of water withdrawn and consumed by power plants from the records of the DRBC that collects this information from state environmental protection agencies and from self-reported water use data from facilities as part of the DRBC charging program (personal communication with David Sayers and Kent Barr, DRBC, on February 14, 2013). The dataset generally spans from 1990 to 2011.

We analyzed the monthly and yearly trends of water use from 2001 to 2011. As the price of natural gas became less expensive, Edge Moor and Eddystone plants switched their primary fuel source to natural gas from coal.[4] Eddystone discontinued coal

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[4] Generation before the fuel switch to natural gas primarily used coal but also included natural gas and petroleum. Starting in July 2010, Edge Moor discontinued coal-powered generation (EIA, 2013a) and added an additional unit powered by natural gas (Calpine). Though Eddystone halted use of one of two

generation starting in May 2011, so the last 8 months of this dataset represent the transition. Edge Moor transitioned entirely in July 2010, so water withdrawals associated with current natural gas generation are represented in the last 18 months of this dataset. We analyze these months to show current externalities. However, we also analyzed withdrawals prior to this fuel switch because I&E data was collected during coal generation, and the impact of I&E is proportional to the amount of water withdrawn. Current withdrawals per kWh are twice those of coal generation.

We also analyzed withdrawals for years in which Salem conducted I&E studies. One study was conducted prior to 2001, so we analyzed withdrawal of years 1994 and 1998-2000, excluding years 1995-1997 because Salem was shut down (UCS). In contrast with Edge Moor, withdrawals at Salem are nearly 80% of past withdrawals per kWh.

We estimated the cost of withdrawals if assigned a proxy value: the price power plants would pay if they needed to buy water from a supplier (such as in the case they cannot claim a riparian right to withdraw water). Of water suppliers regulated by the state of Delaware, rates for water range from $2.74/thousand gallons to $8.71/thousand gallons for drinking water.[5] The average rate for residential customers is $6.08/thousand gallons. Commercial customers on average pay $4.70/thousand gallons. United Water is the largest supplier of non-potable water for industrial use and sells this at a rate lower than average drinking water at $3.1697/thousand gallons for the first 1.4 million gallons of water withdrawn in a month. Beyond the first 1.4 million gallons within a month, the price is $2.3659/thousand gallons (United Water, 2011). These values are in 2013 dollars. We used this rate, and nearly all water is valued at $2.3659/thousand gallons because the first 1.4 million gallons per month represent less than 0.02% of the water.

A percentage of this price (11%) is what consumers pay for the water supply itself, based on a sample water company's expenses provided by the Delaware Public Service Commission (DEPSC) (personal communication, Robert J. Howatt, Executive Director, DEPSC, February 17, 2013). This excludes the costs of pumping the water, treating it, and transporting it and is the cost of the water company's plant assets (including access to water) and rate of return. For an estimate of the breakdown of contributions (e.g., capital costs, pumping, distribution, operations and maintenance) to this cost see Technical Appendix E. This portion for water supply (11%) is $0.34867/thousand gallons withdrawn for the first 1.4 million gallons and $0.26015/thousand gallons for subsequent withdrawals. We use this portion to calculate how much the power plants would be paying for the water itself.

The water withdrawal externality follows as a calculation based on monthly gallons withdrawn per kWh multiplied by the value of water (see Equation 1). This externality considers all water that has been withdrawn regardless of whether the water is returned to the Delaware River after use or evaporated during cooling. We did not assign consumed water a different monetary value due to the complexity in defining the price of water and because consumed water represented less than 1% of water withdrawals.

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units powered by coal in 2011 and the remaining unit in 2012 (Power Engineering, 2009; Exelon, 2014), Eddystone stopped using coal for fuel in May of 2011 (EIA, 2013b).

[5] We contacted water suppliers regulated by the Delaware Public Service Commission to identify their water rates (DEPSC, 2013).

Equation 1. Water withdrawal externality.

$$\frac{monthly\ gallons\ withdrawn}{monthly\ kWh\ produced} \times \frac{proxy\ value\ (\$)}{gallon} = \frac{water\ withdrawl\ externality\ (\$)}{kWh}$$

2.2.2. Impingement and entrainment externalities

Section §316(b) of the Clean Water Act requires the location, design, construction and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact. Section §404 of the Clean Water Act requires that power plants apply for permits to implement this §316(b) rule through the National Pollutant Discharge Elimination System (NPDES). The EPA promulgated rules that require biological monitoring characterizing the impact of impingement and entrainment caused by cooling water intake structures in adherence to Section §316(b) (40 CFR 125.87). Biological monitoring studies are often required when renewing permits, and we analyzed reports characterizing I&E at Salem, Edge Moor, and Eddystone power plants (see Technical Appendix B).

We focused on impacts from I&E on nine fish species: weakfish (*Cynoscion regalis*), Atlantic croaker (*Micropogon undulatus*), striped bass (*Morone saxatilis*), blue crab (*Callinectes sapidus*), alewife (*Alosa pseudoharengus*), and blueback herring (*Alosa aestivalis*), American shad (*Alosa sapidissima*), Atlantic menhaden (*Brevoortia tyrannus*), and bay anchovy (*Anchoa mitchilli*). These species occupy the estuarine environment for all or part of their lifecycle (see Technical Appendix D) and represent most of the species that were consistently characterized among most biological monitoring studies and have been historically fished by commercial and recreational fishermen. Some species have experienced stress on their populations. Currently, alewife and blueback herring fisheries are closed (NJ DEP, 2013; MD DNR; DNREC, 2012) and are species of concern (NOAA, 2013). Though currently fished in the Mid-Atlantic, the American shad population is also severely impacted (Roe, 2011). Currently, striped bass are a recovering species whose population has been increasing over several decades due to regulatory measures. Concurrently, the weakfish population has been declining, partially due to the increase in the striped bass population that preys on weakfish (personal communication with Dr. Kahn of DNREC on September 26, 2013).

These species represent a very small subset of the total species killed by I&E. Species without any direct use (e.g. commercial and recreational harvest) account for 97.3% of I&E mortality (EPA, 2011) and are rarely analyzed in biological monitoring studies, despite providing value to the ecosystem. This means we have no record of the impact of I&E of several hundred species that are regularly killed. Because the vast majority is not represented in the data and is not monetarily quantified, this analysis conservatively represents economic losses associated with I&E.

We monetized impact to fish if directly impacting commercial and recreational fisheries and made the following assumptions:

- We analyzed estimates of fish killed annually rather than raw data of fish killed per sampling period because seasonality can influence the impact of I&E. Water intake frequency and velocity, weather, fish population dynamics, fish migrations, and fishing pressure can vary by season. Still, these estimates do not account for recruitment that would have ensued by these fish having offspring, further enhancing populations. As such, these estimates are conservative.

- We divided the estimates of fish killed at each power plant by the plant's kWh produced in the year(s) in which the I&E study was conducted.
- We adjusted estimates for changes in water withdrawals so they represent current generation ("adjustment factor" in Equations 2 and 3). Salem presently uses 80% of the water per kWh used in 1994-2000. Edge Moor uses twice the amount of water currently compared to prior to the fuel switch from natural gas to coal.
- We did not use data during years in which a power plant was shut down.
- Monetary values are converted into 2013 dollars using the Consumer Price Index.

2.2.2.1. Total non-monetized I&E impact on fish of commercial and recreational use

Estimates of the total numbers of fish lost to I&E were reported in several studies; however, only studies conducted at Salem (PSE&G,1999; PSE&G, 2006) contained enough information to calculate the impact as number of fish killed per unit of energy produced: estimates of the total number of fish lost annually for each species and lifestage (egg, larvae, juveniles, and adults). We focused on the most recent Salem report because it represents externalities of current generation.

Eddystone's 2008 report included annual estimates but without lifestage specifications (Kinnell et al., 2008). Furthermore, the data was collected inconsistently at multiple intake screens as a result of regulatory exemptions[6] and we were unable to determine an adequate estimate of fish killed per gallons withdrawn or kWh. Deepwater's 2007 report contained estimates but only for the impacts of impingement (URS Corporation, 2007). Edge Moor's 2002 report (Entrix, Inc., 2002) contained no estimates of total fish killed by both impingement and entrainment.

2.2.2.2. I&E impact to commercial fisheries

From biological monitoring studies, we identified the amount of fish that would have been caught from commercial and recreational fishermen had they not been killed by I&E at Salem (PSE&G, 1999) and Edge Moor (Entrix, Inc., 2002). The reports do not distinguish between the pounds lost to commercial fisheries and recreational fisheries. Because fish have different values in the sectors, we estimated by fish species the percentage of landings that were commercial and recreational through an analysis of landings data from 1981 until present compiled by the Atlantic Coastal Cooperative Statistics Program (ACCSP) (ACCSP, 2013, accessed on November 3, 2013). We queried landings at ports in Delaware, Maryland, and New Jersey, states that likely receive fish caught in the Delaware River estuary. We calculated the ratio of commercial to recreational landings using data since 2002 by fish species, with the exception of blueback herring and blue crab. Only the year 1998 contained data for both commercial and recreational landings for blueback herring. Recreational landings for blue crab were

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[6] The study was conducted when Eddystone's coal-powered units 1 and 2 were in operation, and the natural gas units 3 and 4 were used for peaking power, operating at less than 15% capacity. The study researched the impact of impingement only at the natural gas units 3 and 4 because the coal units 1 and 2 contained wedge-wire screens. These screens are exempted from biological monitoring because they are known to reduce impingement (Kinnell, 2008). Conversely, entrainment was only studied at the coal units 1 and 2 because the natural gas units 3 and 4 only provided peaking power and were thus exempt from biological monitoring (personal communication, Jason Kinnell, November 12, 2013).

not available in the ACCSP but estimates of both commercial and recreational landings were available from state departments of natural resources (see Technical Appendix F).

The Salem study reported only a single average estimate of pounds of fish lost between 1978 to 1998 annually, so we used this number in our calculation of the commercial fishery externality (see Equation 2). The Edge Moor study reported estimates for years 2000 and 2001, and we used data from the year 2001. We noticed that data is incomplete for Edge Moor's water withdrawals in 2000 (they were abnormally low compared to typical water withdrawals in recent years). As such we chose to focus on the year 2001. The average landing price is the average historical commercial value per pound of fish landed based on market landings data since 2002 (ACCSP, 2013, accessed November 3, 2013). See Table 1 for list of commercial values.

Equation 2. Commercial fishery externality.

$$\frac{annual\ pounds\ lost\ to\ fishery}{annual\ kWh\ produced} \times\ adjustment\ factor\ \times \frac{average\ landing\ price\ (\$)}{pound\ landed}$$
$$= \frac{revenue\ lost\ to\ fishery\ (\$)}{kWh}$$

2.2.2.3. I&E impact to recreational fisheries

The same reports that were used to identify the externality to commercial fisheries were used to calculate the externality to recreational fisheries using Equation 3. Recreational fishing has market value but it is not captured in landings data as commercial values are. We estimate recreational values using benefits transfer (EPA, 2002). Recreational fishing is valued in different ways: the willingness-to-pay (WTP) for a fishing trip, the WTP for each fish caught, and the WTP for increased catch rates. WTP values depend on the methodology of the analysis and variations in resource, context, and angler attributes (Johnston et al., 2006); it is important to select values carefully. The value per fish established in the studies ranged widely because they measured different attributes (e.g., value of one extra fish versus value of existing fish). We narrowed our focus to studies that analyzed a fisherman's value of extra fish caught due to fish population improvements (e.g. ecosystem improvements from reduced pollution).

For the benefits transfer, we considered McConnell and Strand (1994) and Hicks et al. (1999) and chose to use the values developed in Hicks et al. because it was the most recent study and thus more likely to be indicative of current values. Furthermore, the values in McConnell and Strand's study were generally higher than the values in Hicks et al., and this could indicate a shift in fishermen's values as fish populations may have changed. Hicks et al. used a random utility model and determined the revealed preference for recreational fishermen's value of catching an extra fish per fishing trip. (It is possible, that the values represented in Hicks et al. may be more representative of a fishermen's value of enhanced fishing experience rather than one additional fish, but we use the "additional-fish" as the metric here). For an explanation of other related studies, see Technical Appendix G. See Table 1 for a list of values.

The estimated fish deaths collected from the biological monitoring studies are in pounds. The Hicks et al. values are per fish. The weight of a fish is proportionate to its length (Wigley et al., 2003). We queried the NOAA recreational fisheries database to obtain the average length of landings of recreational fish for each species by state. We calculated a weighted average length for each state for the same years we used to determine the ratio of commercial to recreational fish (as discussed in Technical Appendix F). We weighted the length of fish from each state based on the percentage of landings found in the state and determined a weighted average length per species. We used the lengths to calculate the expected weight of each species using the function developed by Wigley et al. (2003) ("average pound" in Equation 3).

Equation 3. Recreational fishery externality.

$$\frac{annual\ pounds\ lost\ to\ fishery}{annual\ kWh\ produced} \times\ adjustment\ factor\ \times \frac{recreational\ fish\ caught}{average\ pound}$$
$$\times \frac{revealed\ preference\ value\ (\$)}{one\ additional\ fish} = \frac{revenue\ lost\ to\ fishery\ \ (\$)}{kWh}$$

2.2.3. Cost comparison with mitigation technologies

We compare the costs of externalities currently caused by Edge Moor with the costs of mitigation technologies: retrofitting to recirculating CWIS and offshore wind energy. We focus on Edge Moor because offshore wind energy is likely to replace natural gas and coal before it replaces nuclear energy. Within PJM, the regional transmission organization that provides power to the region, offshore wind is anticipated to provide peaking power while nuclear energy will provide constant base-load power (GE Energy Consulting, 2013). Because Edge Moor and Eddystone no longer use coal, we calculate the costs of current externalities caused by natural gas. We focus on Edge Moor because we have data after it had fully transitioned to natural gas.

We calculate the net present value of total water externalities caused by Edge Moor using equations 1, 2, and 3 at a 3% discount rate over 20 years (typical lifespan of an offshore wind farm). We value water withdrawals using the price of water supply only (see Technical Appendix E). We inflate the price of water by 4% and lost fishery revenues by 3%.[7] We divide the net present value by estimated generation over 20 years to obtain a levelized cost of externalities ($/kWh). We compare this to the levelized cost of retrofitting Edge Moor to a recirculating CWIS (EPRI, 2011).[8] We add the costs of remaining water externalities that are not eliminated by recirculating CWIS because they reduce withdrawals by 93 to 98% (EPRI, 2011). Using the average of the water reductions (96%), we assume that a recirculating CWIS withdraws 4% of the water it withdraws and kill 4% of the fish it kills currently.

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[7] We calculated inflation of water price by calculating the percentage changes in price for non-potable water sold by United Water since 1999 (personal communication with Tom Hubbard, Pubic Relations Manager, United Water on March 13, 2014). We assumed inflation rate for lost fish revenues would be consistent with the percent change in Consumer Price Index over the past 25 years.

[8] We calculate the levelized cost over 20 years using national average cost estimates for retrofitting plants located on oceans, estuaries, and tidal rivers, including capital investment, downtime during retrofitting, and operation and maintenance ($0.0003/kW) (EPRI, 2011). Edge Moor is 725 MW capacity (Calpine), and the net present cost of retrofitting it is $197 million. We determined this cost is $0.012/kWh by dividing the total cost by the expected kWh generation over 25 years based on Edge Moor's average monthly generation when operating on natural gas (56,000,000 kWh).

We also compare costs of externalities to the levelized cost of offshore wind energy. New wind energy developments primarily will face competition from new natural gas plants, which will likely be combined cycle (CC) plants because they are more efficient than single cycle designs. To simulate the choice between offshore wind energy and natural gas CC, we calculate the difference between the levelized costs of these two energy sources (both with and without carbon capture and storage (CCS)) and compare this difference with the costs of externalities at Edge Moor. We assume a 20-year life of each project. The levelized cost of offshore wind energy is $0.155/kWh (Lazard, 2013). The average levelized cost of CC is $0.074/kWh, and the levilized cost of CC with CCS is $0.127/kWh (Lazard, 2013). We estimate the cost of water externalities associated with natural gas CC and CC with CCS by assuming that the externalities are respectively 0.7% and 1.4% of a single cycle natural gas plant with a once-through CWIS.[9]

3. Results

3.1. Water withdrawal and consumption externalities

Average water withdrawals are summarized in

Costs associated with current water withdrawals are represented in Table 4. The total payment is the amount of money these plants would be paying if they had to purchase non-potable water from a supplier. The costs of water supply represent the percentage of this payment that is for water specifically (11%).

Table 2~~Table 2~~ and Table 3~~Table 3~~. While using natural gas, Edge Moor uses twice the amount of water (142 gallons/kWh) than when it operated on the fuel mixture in the past (71 gallons/kWh). Water use at Eddystone has been much higher since May 2011, the month during which Eddystone began the transition to natural gas generation. Though Eddystone discontinued coal starting in May 2011, it did not finalize the transition to natural gas until 2012. Withdrawals associated with the time period of May to December 2011 are eight times historic withdrawals. This should not necessarily be interpreted as withdrawals during typical production, and indeed, may demonstrate how withdrawals can increase during unusual periods such as fuel switching and maintenance. Withdrawals at Salem in 2011 are consistent with the time period of 2001 to 2010 and are comparable to those of Edge Moor and Eddystone when they operated on coal. Salem currently withdraws nearly 80% of what it withdrew between 1999 and 2000.

Costs associated with current water withdrawals are represented in Table 4. The total payment is the amount of money these plants would be paying if they had to purchase non-potable water from a supplier. The costs of water supply represent the percentage of this payment that is for water specifically (11%).

Table 2. Current average water withdrawals of Edge Moor, Eddystone, and Salem.

Power plant	**Primary fuel type**	**Time period**	**Average water withdrawals *(gallons/kWh)***

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[9] The average natural gas CC with a recirculating CWIS uses 0.25 gallons/kWh, and the average natural gas CC plant with CCS uses 0.5 gallons/kWh, which respectively are 0.71% and 1.4% of the water use of an average single cycle natural gas plant with once-through cooling (35 gallons/kWh) (Macknick et al., 2012).

Edge Moor	Natural gas	July 2010-Dec. 2011	142
Eddystone	In transition to natural gas	May-Dec. 2011	839
Salem	Nuclear	2011	57

Table 3. Historic average water withdrawals of Edge Moor, Eddystone, and Salem.

Power plant	Primary fuel type	Time period	Average water withdrawals *(gallons/kWh)*
Edge Moor	Coal	2001-June 2010	71
Eddystone	Coal	2001-April 2011	106
Salem	Nuclear	2001-2010	60
Salem	Nuclear	1994, 1998-2000	77

Table 4. Costs associated with water withdrawals. Total payment is the cost power plants would pay to a water supplier. Costs of water supply are 11% of this cost and exclude maintenance and transportation.

Power plant	Primary fuel type	Total payment *($/kWh)*	Costs of water supply *($/kWh)*
Edge Moor	Natural gas	$0.34	$0.04
Eddystone	In transition to natural gas	$1.99	$0.22
Salem	Nuclear	$0.14	$0.01

3.3. Total non-monetized I&E impact on fish of commercial and recreational use

Table 5 shows the total numbers of fish killed in each lifestage for each species at Salem. Externalities are represented per gigawatthour (GWh) because fractions of numbers of fish are killed per kWh and using GWh shows the externality clearly. The majority of organisms killed are eggs, larvae, and juveniles. Of species studied here, bay anchovy, striped bass, Atlantic croaker, and weakfish appear most affected. We did not attempt to monetize the loss of non-market species killed by I&E.

Table 5. Numbers of organisms killed due to I&E at Salem nuclear plant.

	Current total number of fish commercially and recreationally fished species killed at Salem *(numbers of fish/GWh)*								
	Eggs	**Larvae**	**Juvenile**	**Year 0**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Total**
Weakfish	0.600	1,210	102	92	0.023				1,405
Atlantic Croaker	0	816	17,090	139	1				18,046
Striped Bass	31	11,421	27	5	0.114	0.033			11,484
Alewife	0	356	4	2	0.062	0			362
Blueback Herring	0	52	29						81
Blue Crab				40	41				81
American Shad				2	0				2
Atlantic Menhaden	0	867	77	8	0.009	0.003	0.003	0.002	952
Bay Anchovy	37,374	35,359	2,272	4	14				75,023
Combined Species	**37,406**	**50,080**	**19,602**	**291**	**56**	**0.040**	**0.003**	**0.002**	107,435

3.2. Impacts to commercial fisheries

We analyzed the fish that could have been caught by commercial fishermen had the plants not been operating. We estimate that Edge Moor kills fish (weakfish, Atlantic croaker, striped bass and alewife) valued at $0.0003/kWh (Table 6) and that Salem nuclear plant kills fish valued at $0.0001/kWh for the same fisheries plus blueback herring and blue crab fisheries (Table 7). We were unable to determine impacts at Eddystone because the I&E report at Eddystone did not estimate impact to fisheries. Atlantic croaker and striped bass are most affected at Edge Moor, and Atlantic croaker and weakfish are most affected at Salem.

Table 6. Estimated current externalities on commercial fishing industries by Edge Moor natural gas plant.

	Commercial landings lost at Edge Moor *(lbs/kWh)*	**Commercial revenue lost at Edge Moor *(2013$/kWh)***
Weakfish	0.000009	$0.00001
Atlantic Croaker	0.0002	$0.0001
Striped Bass	0.0001	$0.00006
Alewife	0.000002	$0.000001
Combined Fisheries	0.0003	$0.0002

Table 7. Estimated current externalities imposed on commercial fishing industries by Salem nuclear plant.

	Commercial landings lost at Salem *(lbs/kWh)*	**Commercial revenue lost at Salem *(2013$/kWh)***
Weakfish	0.00005	$0.00006
Atlantic Croaker	0.00003	$0.00002
Striped Bass	0.00001	$0.000006
Alewife	0.000000004	$0.000000002
Blueback Herring	0.00000005	$0.00002
Blue Crab	0.000001	$0.000002
Combined Fisheries	0.00009	$0.0001

3.2. Impacts to recreational fisheries

We estimated recreational fisheries lose monetary benefits from weakfish, Atlantic croaker, and striped bass fisheries at a rate of $0.001/kWh at Edge Moor currently (Table 8). Salem nuclear plant causes losses of $0.0004/kWh (Table 9). Losses of Atlantic croaker and striped bass are the main external costs to fisheries caused by Edge Moor. For the Salem plant, weakfish have more of an influence, and striped bass is not affected as much.

Table 8. Estimated current externalities of lost landings and monetary benefits for the recreational fishing industry caused by Edge Moor.

	Recreational landings lost at Edge Moor *(lbs/kWh)*	**Recreational monetary benefits lost at Edge Moor *(2013$/kWh)***
Weakfish	0.00001	$0.00004
Atlantic Croaker	0.0002	$0.0009
Striped Bass	0.0003	$0.0002
Alewife	0.00000007	

Combined Fisheries	0.0005	$0.001

Table 9. Estimated current externalities of lost landings and monetary benefits for the recreational fishing industry caused by Salem nuclear power plant.

	Recreational landings lost at Salem *(lbs/kWh)*	**Recreational monetary benefits lost at Salem *(2013$/kWh)***
Weakfish	0.00006	$0.0002
Atlantic Croaker	0.00003	$0.0002
Striped Bass	0.00003	$0.00002
Alewife	0.0000000002	
Blueback herring	0.00000002	
Blue crab	0.0000001	
Combined Fisheries	0.0001	$0.0004

3.4. Cost comparison with mitigation technologies

We calculated the levelized cost of externalities at Edge Moor operating on natural gas and compared this to the costs of retrofitting to recirculating CWIS and offshore wind energy. Water withdrawals ($0.042/kWh) constitute nearly all of the combined water externalities ($0.042/kWh) (Table 10). Retrofitting ($0.014/kWh) is a third of the costs of combined water externalities (Table 11). The difference between the levelized cost of offshore wind and natural gas CC ($0.081/kWh) is twice the costs of water externalities, but the difference between the levelized cost of offshore wind and natural gas CC with CCS ($0.027/kWh) is about 60% of the cost of water externalities.

Table 10. Estimated levelized cost of current externalities at Edge Moor over 20 years.

Estimated levelized cost of current externalities at Edge Moor ($/kWh)	
Externalities on fisheries	$0.001
Externalities of water withdrawals	$0.041
Combined water externalities	$0.042

Table 11. Levelized cost of mitigation technologies, retrofitting to recirculating CWIS and offshore wind energy. Costs calculated over 20 years of generation.

Levelized cost of mitigation technologies plus costs of unmitigated water externalities ($/kWh)	
Retrofitting to recirculating CWIS	$0.014
Difference between offshore wind and natural gas CC	$0.081
Difference between offshore wind and natural gas CC with CCS	$0.027

4. Discussion

We analyzed a subset of externalities associated with electricity production – water withdrawals for cooling purposes and resulting death of fish. These externalities have not been included in the predominant studies examining externalities associated with electricity production (European Commission, 2003; NEEDS, 2009; NRC, 2010; Muller et al., 2011; Epstein et al., 2011). Though studies have extensively compared water use among energy sources (Keith et al., 2012; Macknick et al., 2012) and acknowledge that renewable energy would greatly reduce this use, rarely has a study discussed the implications of pricing water and fish. Similarly, I&E has been the subject of much study, especially because it has spurred lengthy legal debate (*Cronin* v. *Browner*

898 F. Supp. 1052 1995; *Riverkeeper* v. *EPA* 475 F.3d 83 2007) and because the EPA has attempted to identify the costs of I&E (EPA, 2011). However, I&E has been largely absent in discussion about renewable energy. Pricing water externalities and requiring mitigation allows the market price of energy to reflect part of its true cost, enabling offshore wind energy to become more competitive on the energy market in the Mid-Atlantic region.

4.1. Defining and pricing water withdrawal externalities

Knowing the amount of water withdrawn per kWh is a useful start for understanding the scale of potential ecosystem impacts because impact of I&E is directly proportional to water withdrawals and most water withdrawn is discharged into the ecosystem with reduced quality. Edge Moor natural gas plant currently withdraws 142 gallons/kWh, approximately double the withdrawals when operating on coal. Salem currently uses water more efficiently (60 gallons/kWh) than Edge Moor even though, as the largest generating facility within this region, it consistently withdraws 70% to over 80% of the water withdrawn. Salem withdrew water less efficiently in the past and currently withdraws 80% of its historical withdrawals.

The true cost of water withdrawals becomes less veiled when withdrawals are assigned a price. Although we could not monetize all of effects of withdrawals (disruption to stream flows, returned water of high temperature, low dissolved oxygen, and biocides) and could not define the true social value of water, we used a proxy value—the price of non-potable water for industrial use. A percentage of this price (11%) is what industrial users pay for the water supply itself excluding costs of pumping water, treating it, and transporting it. We argue that power plants' claims to riparian rights to withdraw water are unreasonable because recirculating CWIS exist as an alternative and substantially reduce withdrawals and ensuing externalities. Furthermore, water use is unreasonable because the water use is disproportionate to the frontage of the Delaware River (see Appendix A), and this use causes damages that are in violation of the public trust doctrine (discussed in Section 4.5). Therefore, water withdrawals are externalities (also considered subsidies). If power plants paid for withdrawals with the cost of water supply, Edge Moor would pay $0.04/kWh when operating on natural gas, and Salem nuclear plant would pay $0.01/kWh.

Currently, these power plants pay the DRBC to ensure availability of water, but they do not cover the entirety of the costs of water availability and do not compensate for reduced water quality that directly affects other riparian users, including the public. Edge Moor and Salem currently pay the DRBC 0.1% of the cost of water externalities we have assigned with the proxy value of water supply (see Technical Appendix H).

4.2. Identifying impact to commercial and recreational fisheries

For both commercial and recreational fisheries, the bulk of the fishery externalities caused by Edge Moor are due to impacts to Atlantic croaker and striped bass. For the Salem plant, losses of weakfish have larger influence. This may reflect the spatial distribution of the species: Atlantic croaker might be evenly distributed between the two plants, while fewer striped bass but more weakfish might be found downriver near Salem. Alewife, blueback herring, and blue crab have little influence on the total externalities for commercial fisheries. Although alewife and blueback herring fisheries are currently closed, given their minor effect, the closure of these fisheries does not materially affect our calculations. In total, commercial fisheries lose \$0.0002/kWh at Edge Moor and \$0.0001/kWh at Salem. Recreational fisheries lose \$0.001/kWh at Edge Moor and \$0.0004/kWh at Salem.

It is important to acknowledge the recruitment limitation of these estimates: I&E reports exclude the impact of I&E on recruitment. If a percentage of the population killed would have produced offspring, and a percentage of the offspring were also to reproduce, and so on and so forth, over several generations, the impact dramatically increases. As well, because these monetary estimates also do not include the deleterious effect of high temperature, low dissolved oxygen, biocides, and reduced stream flow, the I&E estimates are conservative.

4.3. Costs of mitigation technologies: recirculating CWIS and offshore wind

We calculated the levelized cost of externalities at Edge Moor operating on natural gas over 20 years and compared this to the levelized costs of retrofitting Edge Moor to a recirculating CWIS and using offshore wind energy. Within the region, offshore wind energy is likely to replace coal and natural gas before it replaces nuclear. In the absence of currently operating coal plants in our geographic scope, we analyzed externalities of natural gas generation and focused on Edge Moor because we had data after it fully transitioned to natural gas. Retrofitting Edge Moor to recirculating CWIS (\$0.014/kWh), incorporating the remaining water externalities, is a third of the costs of combined water externalities (\$0.042/kWh), making retrofitting cost effective.

In the future, if new generation is to be built, a likely choice is natural gas CC with or without CCS because its market price is less costly. However, offshore wind energy is also a future choice, and to simulate the choice between the two sources, we calculated the difference between the levelized costs of these sources with and without CCS. The difference between offshore wind and natural gas CC without CCS (\$0.081/kWh) is twice the costs of water externalities. However, when including CCS technology, the difference (\$0.027/kWh) costs less than water externalities, making offshore wind energy a cost effective mitigation technology of the future. If other externalities such as human health impacts were considered, the benefits of using offshore wind would be much higher. (Climate change externalities are already incorporated with the cost of CCS).

4.4. Benefits of offshore wind energy for wildlife

Elimination of I&E is an additional reason that wind energy provides overwhelming benefits for wildlife compared to conventional energy (Sovacool, 2009; EBF, 2009; Sovacool, 2013). Wind energy mitigates climate change, ocean acidification, and environmental damage from fuel mining and related activities. However, there is concern that wind energy creates other environmental impacts: noise pollution, habitat fragmentation, and collisions of birds and bats. Collisions directly affect wildlife, much like I&E. The number of birds that collide with turbines range between 0.240 birds/GWh to 1.791 birds/GWh, depending on turbine distance from shoreline.[10] When considering

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[10] We examined literature that identifies bird collisions with offshore wind turbines (Desholm, 2003; Poot, 2011; Skov et al 2012; Vanermen et al., 2013). We calculated the collisions per GWh based on the

only the magnitude of organisms killed, Salem nuclear plant kills more organisms, resulting in over 100,000 organisms per GWh when considering all eggs, larvae, juvenile fish, and adults killed. The vast majority of the killed population is eggs, larvae, and juveniles (about 56 one-year-old fish are killed per GWh).

Fish and birds are different organisms, and analysis of their mortality should include consideration of their life histories. Fish spawn thousands of eggs, and only a small amount of these eggs survive to adulthood. Birds lay only several eggs at a time; thus, survival of individual bird eggs is more important for the propagation of the species in comparison to an individual fish egg, which is one among thousands.

Though these organisms have different population dynamics and natural mortality rates, when looking at total wildlife lives killed, Salem's organism mortality rate could be considered approximately 100,000 times as great per unit of energy produced compared with wind energy. Furthermore, considering that 97.3% of the fish species killed are not even considered in this Salem I&E estimate (EPA, 2011), even this astonishing comparative rate is conservative.

Moreover, CWIS also impact birds: fish-eating birds suffer and birds themselves are impinged. During a two-month period, a Wisconsin nuclear plant impinged 74 cormorants, which was 3.2% of the total potential productivity of the species (EPA, 2002). At a New Hampshire nuclear plant, 29 scoters were impinged at CWIS 40 feet below the surface (EPA, 2002), likely because they dove to fed on mussels attached to CWIS (North Atlantic Energy Service Corporation, 1999). Fish-eating birds may be impacted for another reason as well: food supply directly impacts their survival and reproductive success. Some species (e.g. ospreys and loons) depend entirely on fish and cannot substitute other prey for fish (EPA, 2002). I&E could be having effects on bird populations if availability of fish prey is substantially reduced (EPA, 2002).

Energy production impacts wildlife in nuanced and complicated ways, and understanding full impact would require accounting for mortality on a life-cycle basis, which would include mortality from mining and transportation of fuels for the life-cycle impacts of conventional energy. For wind turbines, life-cycle impacts persist as well. Other mortality caused by turbines is currently being researched (long-term impacts from noise pollution impacting marine mammals and fish and habitat fragmentation), but with proper mitigation techniques (sound barriers and proper siting procedure excluding migration regions), it is likely these impacts are mitigated so that populations are not impacted.

Additionally, understanding population effects associated with I&E is complicated. Some studies suggest that I&E may not have great implications at the population level (Barnthouse, 2013; Lohner and Dixon, 2013), but all parties agree that a recurring problem is lack of ecosystem-specific, long-term data on which to base assumptions and construct estimates. No assessment of the cumulative impacts has been

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historical generation of offshore wind farms featured in these studies (NoordzeeWind, 2008; NoordzeeWind, 2010; LORC, 2011a; LORC, 2011b). Generally, turbines close to shore kill both seabirds and migrating shorebirds while turbines farther from shore kill predominately seabirds. Studies of collision rates with offshore turbines have all been conducted in Europe. It is possible that effects may be different in Mid-Atlantic waters but it is unlikely that it would be so different to dramatically influence the ratio of bird deaths to fish deaths by conventional energy.

conducted for the Delaware River estuary specifically, with the exception of an assessment of Salem's substantial effect on the striped bass cohort (Kahn, 2011). Part of the problem is that the impact of I&E in CWA Section 316(b) biological monitoring studies are not communicated effectively. Several reports contain reams of raw data per sampling period for a multitude of species, but do not include estimates about the annualized or long-term I&E impact. The methodologies employed make it difficult to come to reliable conclusions as well. In some cases, fish samples were not collected at the same CWIS intake screens. This procedure fit a permitting requirement but obscured understanding of the comprehensive impact of I&E, which contradicts a fundamental purpose of the CWA. The problem is exacerbated by implementation of the regulatory program in a manner that is tailored to each specific plant, which does not allow for consistent comparison among reports from different plants. Understanding cumulative, ecosystem impacts is crucial to understanding far-reaching impacts. Standardization of I&E studies should be required so that data can be interpreted to understand the impact (e.g., ability to understand comprehensive impact per kWh or gallons withdrawn).

4.5. Responsibilities of the state and implications for offshore wind energy policy

The power plants in the lower Delaware River estuary claim a right as riparian landowners to withdraw water freely. This right is void if withdrawals are unreasonable, such as they detriment the quality and availability of the water. These power plants reduce the quality of the water (including killing fish that inhabit the water) and only partially compensate for availability of the water (DRBC charges cover only part of reservoir expenses). We argue that these water withdrawals are unreasonable because retrofitting to recirculating CWIS is an existing alternative that substantially reduce withdrawals and externalities while still producing electricity at the site. Additionally the proportion of water being withdrawn at these plants is disproportionate to the frontage these plants occupy along the Delaware River. Power plants circulate a volume of water equal to 34% of the river flow; however, their frontage only constitutes 1.1% of the Delaware River (see Technical Appendix A). Reasonable use would be a more proportionate allocation of water for riparian owners; water withdrawals as a portion of the river flow should be in similar proportion to the ownership of land along the water body.

Furthermore, these externalities violate the public trust doctrine. Each state has a public trust doctrine that entrusts a duty to the state to protect state-owned natural resources as a trustee on behalf of the public. State-owned water resources include the water itself and inhabiting fish. States have the fiduciary duty to ensure that the quality of water resources and fish populations is maintained for the public. Power plants of the Delaware River estuary harm these state resources. States can require retrofitting to recirculating CWIS or charge for withdrawals and ensuing externalities. This payment could be a rate for withdrawals and water consumed, taxes on production, or tradable permits. States can also incentivize offshore wind energy as a mitigation technology through tax credits and subsidies.

An additional reason that the public trust doctrine applies is that in state waters, public trust rights must be accommodated in consumptive water rights. This includes that water rights are subject to review and reallocation, no matter how long held, in order to uphold the public trust. These concepts were determined in a case against a city water department that diverted water from a lake, causing environmental damages (*National Audubon Society* v. *The Superior Court of Alpine Valley*, 33 Cal. 3d 419; 658 P.2d 709; 189 Cal. Rptr. 346, 1983). Petitioners challenged their actions, claiming that they were violating the public trust doctrine by causing environmental damages. This means that though the power plants in this analysis have been operating using closed CWIS for decades, their water rights are presently and will always be subject to review and reallocation. Their riparian right to withdraw water can be modified or revoked.

Questioning reasonable use of riparian rights and implementation of the public trust doctrine may be more successful methods of reducing water externalities rather than arguing for appropriate implementation of CWA Section 316(b). Appropriate implementation has been debated in litigation for two decades and has yet to be resolved. In contrast, the public trust doctrine has successfully sought compensation on damages to fish through habitat destruction (*State Department of Fisheries* v. *Gillette*, 27 Wn. App. 815, 621P.2d 764, 1980). This case implied that states have a fiduciary duty to sue those who harm public trust resources, especially fish. This implies that under the public trust doctrine, if the states that border the lower Delaware River estuary determine that state public trust resources of fish and water are imperiled, they are compelled to address that situation, including suing those responsible. Investigation of state-specific rules may also be fruitful, as New Jersey has a statutory requirement that any appropriation of water be for the public benefit. One may argue that water externalities are a public detriment and in violation of the statutory requirement, especially in the wake of alternatives.

Controversy over requiring retrofits (*Riverkeeper* v. *EPA* 475 F.3d 83 2007), alternative energies, and other technological advancements[11] stems from the assumption that high electricity costs should be inherently avoided because we have responsibility to ensure the public is paying reasonable rates for electricity. However, the public does pay these costs now in terms of fish losses, health costs, and others, many just do not know it. Moreover, although offshore wind energy is presently more expensive than natural gas (only considering the electricity price), over time, offshore wind energy projects are projected to have lower costs than market prices (Levitt, 2011). Yes, the offshore wind industry needs to start before this can happen, and one way to enable it, is to level the playing field and require power plants pay for externalities.

Advocates of offshore wind energy can support this process by advocating for policy that mitigates water externalities. Discussing benefits to fish is also useful in stakeholder engagement. For example, elimination of I&E may alleviate some concerns that fishermen have about offshore wind. Offshore wind farms occupy large areas of the marine space, and it is unlikely that fishermen will be allowed to fish within these areas. Fishermen often perceive excluding fishing from these areas as an obstacle (Mackinson et al., 2006) because they are concerned that their harvests will decline and businesses suffer. However, compared to the impact of conventional energy, deployment of offshore

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[11] Other I&E reduction techniques exist to reduce the number of fish killed at the intake: traveling screens, behavioral barriers such as air-bubble curtains, wedge-wire screens, and variable speed pumps (MLML, 2008). The costs of these techniques were not included in this study because the costs are very site-specific as well as ensuing reductions in I&E. Some of the plants in this analysis have some of these reduction techniques. Costs and benefits associated with these reduction techniques for plants in the Delaware River estuary could be avenues for further research to better identify the true costs of energy.

wind energy may improve fish stocks. Along with other studies (EPA, 2011), we have demonstrated that fisheries have financial gains when I&E is reduced. For example, assuming most recent annual generation (kWh) and externality rates in Tables 6-9, Edge Moor annually causes commercial losses amounting to $31,000 and recreational losses at $156,000. Salem causes commercial losses of $15,600 and recreational losses of $62,300. In addition, offshore wind energy produces artificial reef effect (Leonhard and Pedersen, 2006) and protects fish habitats, as a result of no fishing allowed within offshore wind sites. Presenting these benefits as trade-offs for reduced fishing area may appeal to fishermen.

5. Conclusion

Conventional energy withdraws water and kills fish through I&E, causing several externalities on water health. Withdrawals disturb ecosystems by moving millions of gallons of water a day through CWIS, removing water due to evaporation, and discharging water of reduced quality. I&E kills fish and shellfish, including those that would have been caught by commercial and recreational fishermen, and potential revenues for fisheries are lost. Power plants claim a right as riparian owners to withdraw water freely. This right is valid only if water use is reasonable, ensuring quality and availability for all riparian users, including the public. Because alternatives exist (recirculating CWIS) that substantially reduce withdrawals and externalities, water withdrawals are disproportionate compared to frontage property, and water rights are subject to review and reallocation, we argue that the water withdrawals are unreasonable and should be mitigated by the state. To fulfill this duty, the state can charge for water, tax for fish deaths, or require retrofitting to recirculating CWIS, which costs less than water externalities. The state can also incentivize offshore wind energy as a mitigation technology through tax credits and subsidies. Natural gas CC plants are a likely energy choice in the future; however, we demonstrate that the cost differential between offshore wind energy and natural gas CC with CCS costs less than water externalities, making offshore wind energy a cost effective mitigation technology. If all other impacts (water quality, fish population impacts, consumption of water, human health, environmental concerns) were monetized, it is likely that offshore wind energy is cost-effective even when CCS technology is not included in the price of natural gas CC. We demonstrate that conventional energy causes substantial water externalities, and pricing these could significantly influence the energy market.

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Technical Appendix

A. *Water withdrawals as a portion of the Delaware River*

The power plants within the study region circulate a volume of water equivalent to the combined mean annual freshwater discharge (ft^3/s) of the Delaware River, Schuylkill River, and Brandywine Creek. Based on data from Trenton, New Jersey, Philadelphia, Pennsylvania, and Wilmington, Delaware, the average of the cumulative discharge over the past 30 years is 15,700 ft^3/s with a standard deviation of 4,100 ft^3/s (USGS, 2014). The discharge ranges from 11,500 ft^3/s to 19,800 ft^3/s, depending on environmental factors such as annual precipitation. We divided water withdrawals of Edge Moor, Eddystone, and Salem by the river flow, and determined that the power plants combined circulate a volume of water equivalent to an average 34% of the combined mean annual discharge, and this ranges between 27% to 47%. Discharges from facilities including treated municipal wastewater and other power plants are also discharged into the region, so the plants do not circulate only freshwater in the CWIS.

These power plants each occupy about a mile each of frontage along the Delaware River based on analysis of maps. (Approximate frontage of Salem is 1.175 miles; Eddystone, 1.313 miles; and Edge Moor, 1.230.) The entirety of the Delaware River is 330 miles (DRN, 2010). Combined the power plants comprise 1.1% of the frontage of the entire Delaware River. Power plants circulate a volume of water equal to 34% of the river flow; however, their frontage only constitutes 1.1% of the Delaware River

B. *Biological monitoring studies*

We contacted the Pennsylvania Department of Environmental Protection, DNREC Division of Fish and Wildlife, and New Jersey Department of Environmental Protection, Division of Water Quality, and requested biological monitoring studies conducted by power plants within the Delaware River and Chesapeake Bay regions and any river systems between the two regions. We chose to focus on the plants along the Delaware River. Plants along the Delaware River that had reports were Fairless Hills (Normandeau Associates, Inc., 2008), Portland Generation Station (AECOM Environment, 2008), Salem nuclear plant (PSE&G, 1999; PSE&G, 2006), Eddystone natural gas plant (Kinnell et al., 2008), Edge Moor natural gas plant (Entrix, Inc., 2002), Deepwater Generating Station (URS Corporation, 2007), and Delaware City Refinery, which does generate small amounts of electricity for industrial use in addition to refining petroleum (Normandeau Associates, Inc., 2001). We found that species composition and abundance depicted at plants differed upriver sites north of Eddystone. Fairless Hills and Portland Generation Station are power plants located farther up the Delaware River. A study at Fairless Hills reported similar species but in different abundances and included other species not depicted in reports within the lower Delaware River estuary (Normandeau Associates, Inc., 2008). A study at Portland Generation Station had only one species in common with those studies at plants in the lower river (AECOME Environment, 2008). As such, we chose to focus on the lower Delaware River estuary.

We did not use data from Deepwater Generating Station because this analysis included estimates of fish impacted due to impingement only. We did not use data from the Delaware City Refinery because the electricity produced is only for industrial use.

C. *Power plants within geographic scope*

The following table lists power plants that withdraw water from the Delaware River that are within the geographic scope of this study. Other plants not listed here are also located along the Delaware River, but there is no record of water withdrawals at these plants because they either do not withdraw water from the Delaware River or produce small amounts of electricity for industrial use (personal communication with David Sayers, Delaware River Basin Commission, February 14, 2013).

Table 12. Power plants that withdraw water from the Delaware River within geographic scope (Calpine Power Plants; EIA, 2014; Exelon, 2014; Sayers and Barr, 2012; NextEra Energy Resources).

Facility	Fuel	Capacity (GW)	CWIS	State
Eddystone Generating Station	Natural Gas, Petroleum	0.820	Open	PA
FPL Energy Marcus Hook	Natural Gas	0.750	Closed	PA
Logan Generating Company LP	Coal	0.225	Closed	NJ
Hay Road*	Natural Gas, Petroleum	1.130	Closed	DE
Edge Moor	Simple-Cycle: Natural Gas	0.725	Open	DE
Deepwater	Natural Gas	0.158	Open	NJ
PSEG Hope Creek Generating Station	Nuclear	1.174	Closed	NJ
PSEG Salem Generating Station	Nuclear	2.360	Open	NJ

*These plants use combined-cycle technology.

D. *Estuarine habitats of species within analysis*

Weakfish inhabit the surf, sounds, inlets, bays, channels, and saltwater creeks (McClane, 1978). They reside in estuaries but do not enter freshwater (McClane, 1978). Atlantic croaker adults reside in estuaries associated with the eastern Atlantic ocean in the spring and leave in the fall to migrate to the Gulf of Mexico for spawning (McClane, 1978). Postlarval and juvenile Atlantic croaker migrate into estuaries and return to the ocean as adults of one year of age (McClane, 1978). Striped bass are anadromous (McClane, 1978) as well as alewife and blueback herring (MD DNRa), spawning in estuaries and inhabiting oceanic waters as adults. Blue crab prefer benthic habitats and can reside in a wide range of salinity from freshwater to full saline waters (MD DNRb). American shad are anadromous species that live most of their lives in the ocean and migrate along the coast from the mid-Atlantic during the winter to Nova Scotia during the summer (DRBC, 2013a). Atlantic menhaden are typically coastal species that migrate south to spawn in the fall and form large schools in estuaries and near-shore ocean during the winter (ASMFC, 2014). Bay anchovy are small marine fish that are abundant in coastal waters (McClane, 1974).

E. *Breakdown of costs associated with non-potable water for industrial use*

The DEPSC provided a breakdown of costs that reflect the costs of non-potable water for industrial use. The DPSC analyzed an unnamed water company, and 31% of the costs were for supply, pumping, and treatment of water and 69% were for distribution. Supply of water itself including plant assets, access to water, and rate of return constitutes 11% of the rate. The DEPSC cautioned that this ratio can vary greatly among water companies. Some water companies need to maintain wells and storage tanks, while others use surface water collections in reservoirs. The quality of water can vary which leads to significant treatment costs. These factors can significantly change the input and ratio of costs (personal communication, Robert J. Howatt, DEPSC, February 17, 2014).

F. Ratio of commercial and recreational landings

We accessed landings data from the ACCSP (ACCSP, 2013, accessed on November 3, 2013). We queried landings at ports in Delaware, Maryland, and New Jersey because these are states that would likely receive landings from fish caught within the Delaware River estuary. We determined the percentage of landings that were commercial or recreational for each year to calculate an average ratio for each species. We analyzed this ratio for each species over time from 1981 until 2012.

Prior to 2002, for Atlantic croaker and striped bass fisheries, the ratio fluctuated greatly. Since 2002, those ratios have been consistent. For this reason, we calculated an average ratio based on landings data since 2002 for those two species. The ratio for the weakfish industry has fluctuated from year to year over the entire period from 1981 to 2012. To be consistent with our analysis of the other two species, we also use an average ratio since 2002 for weakfish. The unpredictable fluctuation may be explained by a steady decline in the weakfish population in the Delaware River estuary since the 1980s. This decline is partially due to the increase of the striped bass population that preys on weakfish (personal communication with Dr. Kahn of DNREC on September 26, 2013).

The ratio trends for alewife and blueback herring were difficult to define because the landings data is sparse over the time period of 1981 to 2012. Since 1981, even though commercial landings are consistently reported, only ten years have reports of recreational landings of alewife. Two of these years are in the time period since 2002. To be consistent with the ratios of the other species, we chose to take the average ratio for the two years since 2002 (2002 and 2006). For blueback herring, there is less data available. While landings are reported sparingly for separate years, only the year 1998 has a report of both recreational and commercial landings, so we used the ratio from this year. We did not average the sparse reported landings data because we could not assume that the blueback population would be the same year to year.

We acquired estimates of blue crab landings at DNREC, Delaware Division of Fish and Wildlife (personal communication, Richard A. Wong, January 9, 2014) and at the Maryland Department of Natural Resources, Fisheries Service (personal communication, Kelly Webb, February 14, 2014). The data from DNREC contained estimates of landings from 1973 to 2012 for Delaware and New Jersey. For Delaware, recreational harvest from 1973-2007 was calculated as 2.5% of the non-dredge commercial harvest based on results from a Division of Fish and Wildlife survey conducted in 1996-1997. Since 2008, the recreational landings estimate was calculated as 4% of the non-dredge commercial harvest, based on results from a more recent telephone/intercept survey conducted in 2008. In New Jersey, annual recreational harvest was calculated as 20% of the commercial non-dredge hard crab landings from May to October based on the results of a telephone/intercept survey conducted in 2005. The Maryland DNR data estimated that recreational blue crab harvest was 8% of total commercial harvest until 2007. Since 2008, there has been a ban on recreational female harvest so recreational harvest estimates were based on the male commercial harvest. Like the Atlantic croaker and striped bass fisheries, the ratio of landings was consistent since 2002, so we chose an average ratio from this time period.

Table 13. Ratio of commercial to recreational landings for selected species.

Harvested Species	Commercial (%)	Recreational (%)	Years Selected

Weakfish	43%	57%	2002-2012 average
Atlantic Croaker	56%	44%	2002-2012 average
Striped Bass	24%	76%	2002-2012 average
Alewife	96%	4%	2002 and 2006 average
Blueback Herring	73%	27%	1998
Blue Crab	93%	7%	2002-2012 average

We also attempted to determine a ratio for bay anchovy because there is record of I&E impacts to bay anchovy within several biological monitoring studies. We had three years of data from the ACCSP for commercial landings and queried recreational landings data from the NOAA recreational fisheries queries database (NOAA). When we found that we could not query sufficient data at specific states, we queried for the Mid-Atlantic region and found marginally better results. No year contained both commercial and recreational landings and thus we could not calculate an accurate ratio of commercial to recreational landings. Extrapolating from available information was unsuccessful and thus we did not include bay anchovy in our analysis.

G. Other recreational fishing valuation studies

In addition to McConnell and Strand (1994) and Hicks et al. (1999), we analyzed several other studies that value different aspects of recreational fishing. Whitehead and Aiken (2000) used contingent valuation to determine the willingness-to-pay (WTP) for recreationally fished striped bass. We did not use this study because the analysis did not determine the WTP for an *additional* striped bass. Agnello (1989) studied the WTP of an additional fish for the first fish and the average of subsequent fish. The study focused on bluefish, weakfish, and summer flounder, and the resulting values depended on the model used. We did not use this study because it was published several decades in the past and was representative of different fish populations than today. Similarly, Norton et al. (1983) also investigated the value of an additional striped bass fish caught, but we did not use this study because it was published several decades before our analysis. Schuhmann (1998) assessed the WTP for an additional 25% increase in recreational catch. We did not use this study because it was not useful for our analysis, given that we had data consisting of pounds of recreational fish lost, rather than percentages of additional harvest per fisherman.

H. Analysis of payments to the DRBC to compensate for availability of water

The DRBC typically charges power plants along the Delaware River $0.80/million gallons of water withdrawn and $80/million gallons of water consumed. Analysis of 2011 charges (DRBC, 2012b) shows that Edge Moor, Eddystone, and Salem do not pay the entirety of this rate (Table 14).

Table 14. Payments to the DRBC for water availability in 2011.

	Percentages of typical DRBC charges	**2013$/kWh**
Edge Moor	29%	$0.00004/kWh
Eddystone[+]	86%	$0.0005/kWh
Salem	16%	$0.00001/kWh

+Eddystone was in transition to natural gas starting in May of this year.