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Integrating water resources and power generation: The energy–water nexus in Illinois

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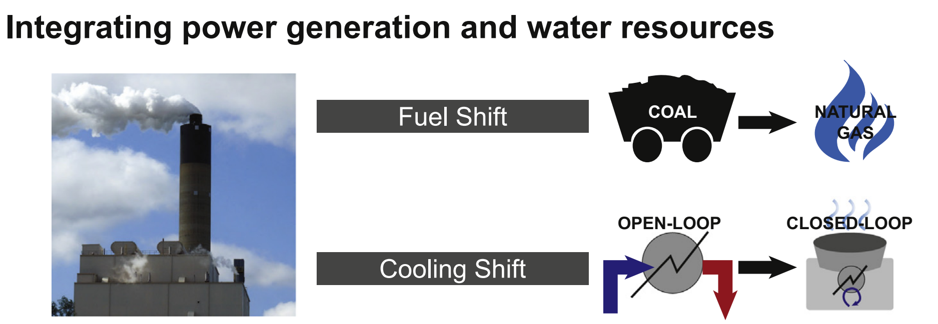
HIGHLIGHTS

- We quantify the water withdrawal and consumption for power generation in Illinois.
- A shift from coal to natural gas decreases water withdrawal and consumption.
- Simulated closed-loop cooling decreases withdrawals, but increases consumption.
- Moderate water prices can economically motivate cooling system retrofits.

GRAPHICAL ABSTRACT



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ABSTRACT

Thermoelectric power plants contribute 90% of the electricity generated in the United States. Steam condensation in the power generation cycle creates a need for cooling, often accomplished using large amounts of water. These large water requirements can lead to negative consequences of power plants dialing down or shutting down during times of low water availability. Consequently, water constraints can translate into energy constraints. Projected future population growth and changing climate conditions might also increase the competition for water in many areas, motivating a resource accounting analysis to both establish a baseline of current water requirements and simulate possible impacts from future water and energy management decisions. Our analysis of the current water demands for power generation, focused on the state of Illinois, combined existing digital spatial datasets with engineering basic principles to synthesize a geographic information systems (GIS) model of current and projected water demand for thermoelectric power plants. We evaluated two potential future cases based on water use implications: (1) a shift in fuel from coal to natural gas, and (2) a shift in cooling technology from open-loop to closed-loop cooling. Our results show that a shift from coal-generated to natural gas-generated electricity could decrease statewide water consumption by 0.10 billion m^3/yr (32% decrease) and withdrawal by 7.9 billion m^3/yr (37% decrease), on average. A shift from open-loop to closed-loop cooling technologies could decrease withdrawals by an average of 21 billion m^3/yr (96% decrease), with the tradeoff of increasing statewide water consumption for power generation by 0.18 billion m^3/yr (58% increase). Furthermore, we performed an economic analysis of retrofitting open-loop cooling systems to closed-loop cooling, revealing an annual cost between \$0.58 and \$1.3 billion to retrofit the 22 open-loop cooling plants considered, translating to an effective water price between \$0.03 and \$0.06/m^3. The synergies and tradeoffs between water resources and power generation yield interesting implications for integrated decision making and policy in Illinois and elsewhere.

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1. Introduction

Energy and water are closely related: energy is needed for water, and water is needed for energy. Water is needed for fuel mining and refining, energy crop irrigation, producing hydroelectric power, and cooling thermoelectric power plants. Energy is also needed to collect, treat, distribute, and heat water for municipal, industrial, and agricultural uses. Additionally, a large amount of energy is required to collect, treat, discharge, and reuse wastewater. This intrinsic relationship is commonly known as the energy–water nexus [1–13].

The thermoelectric power sector in the United States is highly dependent on water for cooling, representing a significant branch of the energy–water nexus. These power plants – depending on nuclear, coal, natural gas, and/or biomass fuels, geothermal resources, or concentrated solar power – require large amounts of cooling water [1–4,7,14], representing 38% of the U.S. freshwater withdrawals in 2010 [15]. As climate change is projected to increase the frequency and severity of droughts in the United States [16], water resources will likely become further constrained. Additionally, both water and energy will likely be in higher demand in the future as the U.S. population is projected to grow from 317 to 400 million by 2050 [17]. Competition is increasingly likely between power plants and other water users in water-stressed areas of the United States and in other locations globally.

While the nexus between power generation and water demand is projected to face additional challenges in the future, power plant cooling technologies and fuel types can have a significant impact on the water intensity of electricity [1,3,18,19]. For example, water demand in the thermoelectric power sector can be reduced by implementing advanced or alternative cooling technologies such as cooling towers [2,20]. In addition to reducing water withdrawals, these alternative cooling technologies can lessen some of the environmental concerns associated with conventional cooling systems [20]. Nuclear and coal-fired power plants are generally more water intensive than natural gas plants [2,14], such that a fuel shift could also reduce water demands.

A baseline evaluation of current water and energy use is motivated by a demand for efficient resource management decisions. In this analysis, we outline a methodology to develop a baseline of current water requirements for thermoelectric power plants, using the state of Illinois as testbed. We also present scenario and economic analyses to simulate impacts of future energy and water decisions, with a summary of associated policy implications.

2. Background

Access to water is an important requirement for thermoelectric power plants. Power plants using a steam cycle deliver 90% of the electricity in the United States; the remainder of the electricity is provided by hydroelectric and other renewable sources [21]. In a typical thermoelectric power plant, heat is created through the burning of fuel, from nuclear reactions, directly from the sun, or geothermal heat sources to boil highly purified water to generate steam. The high-pressure steam turns a steam turbine connected to a generator, which produces electricity. Steam exiting the turbine is condensed in a heat exchanger using water (or air) as the cooling fluid, and is then returned to the boiler to repeat the process. In wet cooling systems, the warmer cooling water is either directly returned to the source (open-loop) or recirculated (closed-loop).

Different types of cooling systems can have considerably different water requirements. To understand these implications, it is important to distinguish between the terms water *withdrawal* and *consumption*. Water withdrawal is defined as water diverted from a surface water or groundwater source that might or might not be returned. Water consumption is water that is not directly returned to the original source, often due to evaporation. Consumption is a subset of withdrawal, with water consumption mathematically equal to the difference between water withdrawal and return flow. Both withdrawal and consumption are relevant for the power generation industry. Water withdrawal volumes are important for various reasons, as withdrawal rates from surface waters influence the richness and diversity of fish and aquatic life negatively affected by intake structures and thermal pollution. Power plants depending on groundwater for cooling place additional strain on aquifers with increased withdrawal rates. Furthermore, many states define water rights in terms of water withdrawal, meaning those volumes are not available for allocation to other high-value water users or environmental needs. Withdrawal volumes are critical for power generation because if the quantity demanded is not available, plants might be forced to shut down or curtail operations. Water consumption is also important because water that is evaporated is not available for other users in the same watershed. Different cooling technologies have vastly different withdrawal and consumption implications; concerns over the relative importance of water withdrawal versus consumption is often highly dependent on local characteristics [14,22].

Before 1970, the majority of U.S. thermoelectric power plants applied open-loop (or once-through) cooling methods due to the ease of implementation, high efficiency, and overall cost-effectiveness [23]. Open-loop cooling systems withdraw large amounts of water from a water source, and pump that water to a condenser where heat is transferred from the steam to the cooling water. The cooling water is subsequently discharged to the receiving water source at a higher temperature. Since open-loop cooling systems return nearly all the water withdrawn, water volumes consumed via evaporation are typically small in relation to withdrawals. Despite its simplicity, this technology can have unintended and detrimental effects on the ecosystem of the water source [24]. Impingement and entrainment of fish and aquatic life can occur at the intake structure. Impingement occurs when organisms become trapped against the intake screen as a result of the high flow rates, often resulting in asphyxiation, starvation, and/or death. Smaller organisms are subject to entrainment when aquatic life is sucked through the entire cooling system, including the pumps and condenser tubes, and discharged back to the source water. These small organisms are often the most fragile, typically fish eggs and larvae. Additionally, thermal pollution can be harmful to fish and aquatic life at the point of discharge. Thermal plumes decrease the dissolved oxygen in the receiving water and cause significant changes to ecosystem compositions and decrease biodiversity [25].

As a result of regulations in the Clean Water Act in 1972, new power plants have shifted toward closed-loop cooling techniques, which recirculate water and minimize the environmental externalities. Closed-loop cooling is an alternative cooling technology that recirculates water through a cooling component, typically a wet cooling tower or cooling reservoir. Some water is returned to the source in the form of blowdown in order to control the buildup of dissolved minerals in the recirculating water, while the remainder is consumed via evaporation. Due to the recirculating nature of closed-loop cooling, these systems withdraw less than 5% of the water withdrawn by similarly sized open-loop systems [14]; however, most of the water is consumed via evaporation, such that on average, closed-loop cooling systems consume more water per megawatt-hour than similarly sized open-loop systems. Despite the additional water consumption, closed-loop cooling systems can significantly reduce the environmental damages associated with open-loop cooling. Decreased rates of impingement,