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Balancing marine ecosystem impact and freshwater consumption with water-use fees in California's power markets: An evaluation of possibilities and trade-offs

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HIGHLIGHTS

- Ocean water withdrawal fees of $10–120/acre-ft simulated for California's 2014 power markets.
- Fee schemes could reduce ocean water use by 11% overall.
- Withdrawal reductions of 9% are possible without increasing freshwater use.
- Wholesale electricity price increases of 5–10% concentrated in Northern California.
- NO_x and SO_2 emissions increases concentrated in the Northern San Joaquin and Sacramento Valleys.

ABSTRACT

This study examines the use of water-use fees in California's bidding-based power markets to balance freshwater conservation and reduction of the marine ecosystem impact of coastal once-through-cooled power plants. An hourly power dispatch is simulated using the state's 2014 demand and generation capacity data. Fees on ocean water withdrawals of $5–120/acre-ft are simulated in three scenarios that test the grid's ability to simultaneously mitigate its impact on marine ecosystems, conserve freshwater, and incentivize recycled water use. Although fees modeled represent a small share of generator fuel costs, results show that they trigger declines in ocean water withdrawals of up to 11% that are almost always cost-effective if accounting for effects on system-wide fuel costs and CO_2 emissions. An appropriately designed fee-structure reduces ocean water withdrawals by 9% without increasing freshwater consumption elsewhere. Wholesale electricity price increases of 5–10% are concentrated in Northern California, and marine ecosystem benefits are partly offset by increases in NO_x and SO_2 emissions inland. Overall, this study finds that water-use fees could be an effective strategy for reducing the marine ecosystem impacts of California's power sector, particularly because they can also address short term fluctuations in freshwater scarcity. Keywords: Energy-water nexus, once-through cooling, scarce water, environmental pricing, energy policy, electricity dispatch, power systems.

1. Introduction

Water and energy resources in the arid U.S. Southwest are closely linked. In California, energy used over the water supply and end-use cycles is equivalent to roughly 19% of electricity generated [1]; similarly the USGS estimated that 17% of all water withdrawals in the state in 2010 were for thermoelectric power plant cooling, the vast majority of which consisted of ocean water [2]. Population growth is expected to drive increases in energy demand and power sector water use [3–5], increasing pressure on California's freshwater resources. At the same time, since 2010 the state's Water Resources Control Board has planned the shut-down or conversion of 19 coastal once-through cooled (OTC) power plants to limit their impact on oceanic and estuarine ecosystems [6]. This study investigates the use of water-use fees in California's power markets as an alternative, price-based strategy for managing marine ecosystem impacts that could simultaneously address short-term

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water conservation objectives.

California's power sector uses a variety of water sources subject to overlapping policy objectives. Since 2003, the state has actively encouraged its thermoelectric power plants to use reclaimed water for cooling because it is considered drought resistant [7]. Indeed, by 2015, half the thermoelectric generation facilities of more than 75 MW capacity in the state used recycled or reclaimed water [8]. Passage of the Sustainable Groundwater Management Act in 2014, and the severity of recent drought conditions, which lead to California's first mandatory urban water use restrictions in 2015, highlight the critical nature of its freshwater scarcity, and the importance of aligning its water and energy policy objectives [9].

Much work on integrated energy supply planning has focused on the water use effects of investments in, or upgrades to new and existing generation capacity. Studies have used long-term energy modeling to examine the water use impacts of emissions reduction alternatives [10–15] or investigated the potential for reducing power sector water use by prioritizing less water-intensive technologies and cooling system retrofits [4,14,16,17] or fuel switching [18]. The use of dispatch protocols to achieve power-system water use objectives with an existing generation fleet is a dimension of water-energy policy that has garnered less attention. A power system's dispatch protocol defines how hourly power output of each electricity generation unit (EGU) in a power system is set. California's electricity grid operates according to a market-based dispatch protocol in which the California Independent System Operator (CAISO) balances power supply and demand by collecting cost bids from suppliers in the market, and scheduling power generation in a unit commitment and dispatch that optimizes cost subject to power flow and load constraints.

Currently, the social costs of water use for power generation are not fully integrated into California's power-system dispatch calculation. Although water use costs are partly included in the market bids of fresh/recycled water-using EGUs, water use rates are usually small compared to power plant operation and maintenance costs [19] and do not necessarily reflect the economic value of water consumption. In the case of ocean water withdrawals, power plants do not pay for their cooling water at all, despite its social cost. A 2005 California Energy Commission (CEC) review, for example, found that impingement and entrainment of fish and other organisms in cooling intake structures had highly deleterious effects on marine ecosystems, with economic losses as high as $9 million per year due to impacts on recreational and commercial fishing alone [20,21]. The nature of these direct impacts (i.e. impingement and entrainment of the marine organisms contained within each unit volume of ocean water), along with thermal impacts from discharges of warm water from power plants [20,22], is such that they increase monotonically with the amount of water withdrawn for cooling. Imposing an ocean water-use fee on California's power sector to reduce ocean water thus presents a more flexible, price-based alternative to its OTC policy as a way of mitigating its impact on marine ecosystems.

Previous work on the use of dispatching strategies to achieve environmental policy objectives in the power sector has demonstrated the benefits of price-based approaches to addressing emissions. Martin et al., for example, examined the use of time- and location-specific NO_x emissions pricing in the PJM Regional Transmission Organization in the Eastern US and found that significant reductions in NO_x emissions were possible on hot summer days when ozone formation was most likely [23]. Other studies have found that pricing CO_2 and NO_x emissions in power networks could lead to significant, instantaneous emissions reductions resulting from changes in the dispatch order [24,25].

Using dispatch pricing to address power plant water use could similarly produce short-term water savings and would provide the added flexibility of pricing schemes that could respond to spatial-temporal changes in water availability. The costs and benefits of such an approach, however, have not been thoroughly examined. In the first study to strictly consider water-based dispatching, Pacsi et al. [26] simulated a drought-centered unit commitment model that temporarily directed thermoelectric power generation away from drought-stricken areas of Texas, and found that total water consumption could be reduced by up to 7% for a 13% increase in electricity prices. Their model, however, did not incorporate changes to market bids from water use fees. In a 2014 study, Sanders et al. [19] simulated an hourly unit commitment and dispatch using 2011 data from the Texas's grid with water consumption and withdrawals fees of $10 and $1000 per acre-ft and found that power system water consumption could be reduced by up to 23% for a 120% increase in generation costs. Although it considered water use fees, the Sanders study did not model transmission constraints to examine their impact on wholesale electricity prices. To our knowledge, no study has considered water-based dispatching of a power system with a diversified water portfolio, an important omission given the different water use objectives of policy makers with respect to different water source types (for example, freshwater vs. ocean water).

In this study, an hourly optimal power flow dispatch with water-use fees is simulated with a grid-model that captures the main structure of California's power grid. We build on prior "water" dispatching work in several ways. First, we expand on the water-use fee concept by considering tax schemes that target California's multiple water use types and balance several water-use objectives simultaneously, an approach especially relevant to the diversified water portfolio of California's power sector. Second, we use transmission constraints to infer the likely spatial and temporal distribution of the effect of these fees on wholesale electricity prices. The purpose of this analysis is to evaluate the immediate reductions in ocean water withdrawals that could be achieved with a withdrawal fee. In addition, we seek to answer four questions previously unexplored in water dispatching literature using California's power grid as a case study: 1. What reductions in ocean water withdrawals are possible from water use fee schemes designed to avoid increasing freshwater consumption? 2. Are water savings cost effective after accounting for increases in fuel use and increases in CO_2 emissions? 3. What are the impacts on wholesale generation prices and how are they distributed in space and in time? 4. What are the air quality impacts and where are they felt?

2. Materials and methods

This study simulates an hourly power dispatch based on California's electricity capacity and demand for 2014, a critical dry year for the state [27]. We use load data (including network power consumption, transmission and distribution losses, and EGU self-use) from the CEC Energy Assessment Division [28], and generation capacity data from the CEC's Quarterly Fuel and Emissions Report (QFER). Non-thermoelectric renewable generation (hydropower, wind and solar photovoltaic) is taken from the Energy Information Administration (EIA) and CEC Energy Assessment Division estimates of distributed generation [28], and is modeled as negative load. Generator fuel costs are calculated from EGU-level heat rates estimated from monthly generation and fuel use data from the QFER and from EIA fuel price data [29–31]. CO_2, NO_x, and SO_2 emission factors are calculated using estimated heat rates (MMBtu/MWh) and generator-specific emissions factors (kg/MMBtu) from eGRID hourly operational data for 2014, or eGRID'2015 Emissions Factors for Greenhouse Gas Inventories [32], when generator-specific data are unavailable.

Generator cooling systems and water sources are assigned using data from EIA Form 860, the CEC's Quarterly Fuel and Emissions Report, and a 2014 report by Diehl et al. [33] prepared for the USGS. Following recent work [34,35], we link EGU water consumption and withdrawal to the heat content of fuels consumed for electricity generation (i.e. we estimate acre-ft of water used per MMBtu of fuel consumed) in addition to the prime-mover and cooling system configuration of the power plant. This approach accounts for variations in the efficiency of thermoelectric generators of the same prime-mover and cooling system type that will change water consumed or withdrawn per

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