Energy Policy 59 (2013) 235–241

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Is there a water–energy nexus in electricity generation? Long-term scenarios for the western United States

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HIGHLIGHTS

- We model long-run electricity supply and demand for the western United States.
- We evaluate the costs of carbon-reducing and water-conserving scenarios.
- Carbon-reducing scenarios become cost-effective at carbon prices of $50–70 per ton CO_2.
- Water-conserving scenarios are only cost-effective above $4000/acre-foot of water.
- Electricity planning is central to climate policy, but much less so to water planning.

ARTICLE INFO

Article history:
Received 1 May 2012
Accepted 16 March 2013
Available online 28 April 2013

Keywords:
Electricity planning
Water–energy nexus
Western United States

Abstract: Water is required for energy supply, and energy is required for water supply, creating problems as demand for both resources grows. We analyze this “water–energy nexus” as it affects long-run electricity planning in the western United States. We develop four scenarios assuming: no new constraints; limits on carbon emissions; limits on water use; and combined carbon and water limits.

We evaluate these scenarios through 2100 under a range of carbon and water prices. The carbon-reducing scenarios become cost-effective at carbon prices of about $50–$70 per ton of CO_2, moderately high but plausible within the century. In contrast, the water-conserving scenarios are not cost-effective until water prices reach thousands of dollars per acre-foot, well beyond foreseeable levels. This is due in part to the modest available water savings: our most and least water-intensive scenarios differ by less than 1% of the region's water consumption.

Under our assumptions, Western electricity generation could be reshaped by the cost of carbon emissions, but not by the cost of water, over the course of this century. Both climate change and water scarcity are of critical importance, but only in the former is electricity generation central to the problem and its solutions.

1. Introduction

Water and energy are deeply intertwined: production of electricity requires water, and water supply requires electricity. Demand for both is growing, while supply is constrained by limited resource availability, high costs, and the impacts of climate change. These linked problems are sometimes referred to as the “water–energy nexus” (among many others, Scott et al., 2011; Bazilian et al., 2011; see also King et al., 2008). This nexus of problems is of great importance to the western United States, a fast-growing region with limited precipitation and water resources.

On the energy side, hydroelectric power, which generates almost one-fourth of the electricity used in the western United States, is completely dependent on water flows. Fossil fuel and nuclear power plants, the source of most of the region's electricity, need a constant flow of cooling water in order to regulate their internal temperatures and prevent overheating. Utility plans for capacity expansion could, under some scenarios, require so much cooling water that they will worsen summer water shortages in many parts of the country (Sovacool and Sovacool, 2009). The need for cooling water can be reduced, at a cost, by building cooling towers; even more water can be saved, at even greater cost, by switching to a completely closed-loop or “dry cooling” system. On the other hand, a still-experimental new technology, carbon capture and sequestration (CCS), may in the future be able to eliminate greenhouse gas emissions from power plants—but it will also require much more water, raising questions about its feasibility for arid regions such as the Southwest.

On the water side, a lot of energy is needed to deliver water to its users. Nineteen percent of California's electricity is used to provide water-related services, including water supply, wastewater treatment, irrigation, and other uses (Stokes and Horvath, 2009). Water from

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0301-4215/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enpol.2013.03.027

northern California is pumped hundreds of miles, over mountains 2000 feet high, to reach southern California; the energy used to deliver water to a household in southern California is equal to one-third of the region's average household electricity use (Cohen et al., 2004).

In Arizona, the Central Arizona Project delivers more than 500 billion gallons of water per year through an aqueduct that stretches 336 miles and climbs nearly 3000 feet from the Colorado River to Phoenix and Tucson (Central Arizona Project, 2011). The Central Arizona Project is the largest user of electricity in the state, consuming one-fourth of the output of a major coal plant to push water across the desert and up the mountains (Scott et al., 2011).

Numerous studies have examined interactions between energy and water supply. For example, a detailed forecast of U.S. electricity generation through 2030 finds that introduction of a carbon price will cause no change or a modest reduction in water withdrawals, but a significant rise in water consumption (Chandel et al., 2011). In this forecast, a carbon price induces a shift toward CCS at fossil fuel plants, and toward more use of nuclear power; both of these technologies increase water consumption, compared to the existing mix of generation facilities.

Addressing a similar question, we adopt a different research strategy, developing alternative long-run electricity generation scenarios for the western United States—a region that includes the driest and most water-stressed parts of the country.[1] Our scenarios adopt differing generation technologies, based on four differing assumptions about future resource and policy constraints: no new constraints; limits on carbon emissions; limits on water use; and the combination of both carbon and water limits. We then examine a range of prices for carbon emissions and for water consumption, to identify the prices at which each scenario becomes cost-effective (in effect, finding the shadow prices for carbon and water that are implicit in each scenario).

2. Model design

We developed a model of the Western electricity sector, combining the growth of demand with long-term resource choices, technology options, and decisions about the type of future to be pursued. The model examines the entire 11-state Western Electric Coordinating Council (WECC), with changes in demand and generation estimated at the state level. The WECC states are Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming. The purpose of this model is to sketch out how the region's electric demand and supply might evolve over a very long planning horizon (to 2100), and what impacts this evolution might have on electricity cost, carbon dioxide (CO_2) emissions, and water use.

The model estimates demand from 2008 through 2100, driven by population, temperature changes, and assumptions about energy efficiency. For each scenario, the model deploys resources to meet the demand, and estimates required generation, bulk power system costs, CO_2 emissions, and electric-system water consumption. It calculates annual (and for selected data items, seasonal) values in 2030, 2050, 2075, and 2100.

The model is driven by user-specified technology choices, not by a cost-minimizing optimization procedure. Utilizing a least-cost optimization framework over such a long planning horizon would run the risk of basing long-run resource choices on costs and parameters which are likely to change over the course of the next few decades, if not years.

In general, the model makes relatively simple, state-level projections of demand. In contrast, it provides facility-level detail on supply technologies, costs, and plant performance, extrapolated to describe the evolving electricity sector needed to meet demand through 2100 under each of the scenarios.

2.1. Electricity demand assumptions

Electricity demand is modeled at the state level, based on forecasts of population, per capita demand growth, energy efficiency measures, and responses to changing temperatures.

2.2. Population

We use 2005 U.S. Census forecasts to estimate state-wide population growth in each of the 11 states to 2030, and then maintain the same population growth rate to 2050. After 2050, population is held constant through 2100.

2.3. Per capita demand growth

Electric consumers in the United States use increasing amounts of electricity each year. However, the rate of this increase has slowed dramatically in recent years, and California has managed to maintain a nearly zero net growth in electricity use per capita over the last three decades. In fact, according to U.S. Department of Energy estimates (EIA, 2010a), per capita consumption in the West will fall in the residential and industrial sectors, and grow only moderately in the commercial sector. We assume that per capita demand will remain constant at 2008 levels, in the absence of new energy efficiency measures. We also assume that the industrial, commercial, and residential fractions of each state's electricity demand are constant at 2008 levels.

2.4. Energy efficiency

As explained below, each scenario is modeled both with and without an ambitious energy efficiency initiative. The efficiency assumption, when used, is comparable to results achieved by existing energy efficiency programs: per capita consumption is reduced, initially at a rate of 1.06% annually. That rate drops to 0.90% annually after 2030, 0.60% after 2050, and 0.45% after 2075.

2.5. Response to temperature

As temperatures rise and fall above and below a comfort threshold, households and businesses use air conditioning and space-heating to maintain comfort. In addition, some states may have seasonal changes in population, e.g. summer or winter vacationers, creating changes in electricity use correlated with temperature (since per capita demand is calculated using year-round average population). Using monthly consumption estimates for each state (EIA, 2010a,b) and population-weighted monthly average temperatures (NCDC, 2010) we estimated residential, commercial, and industrial consumption per capita in each state as a quadratic function of temperature.[2]

The fitted curves for residential per capita demand versus temperature for five states are shown in Fig. 1. The shape of this

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[1] This analysis was developed as part of a broader study of the effects of climate change and water scarcity on the southwestern United States (Ackerman and Stanton, 2011). The study was supported by a grant from the Kresge Foundation to the Stockholm Environment Institute, where Frank Ackerman worked at the time. The study's background paper on electricity generation (Fisher and Ackerman, 2011) provides additional statistical detail on a number of the results described here.

[2] A quadratic function of temperature fits the data well, with an unweighted average r^2 across the 11 states of 0.86 for residential, 0.81 for commercial, and 0.61 for industrial consumption per capita; the worst fits were for industrial load in some of the smaller states.