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An Input-Output Analysis for the Northeast of the United States

Abstract

As water scarcity and pollution of sources become increasingly severe and widespread, competition over this resource intensifies. Unlike much of the rest of the world, thermoelectric plants in the US are the biggest users of water due to heavy reliance on once-through cooling technology. This cooling technology withdraws large amounts of water and discharges it back almost in its entirety but at higher temperatures. These water withdrawals are increasingly subjected to legislation intended to reduce the effects of thermal pollution. We utilize an interregional input-output model for quantifying the money costs and the shifts in the distribution of power production by state and by technology when withdrawals and discharges of fresh water are restricted. This model allows for the choice among alternative power generation technologies with different cost structures within each state. We analyze a Baseline scenario for 2010 and alternative scenarios that impose constraints on water withdrawals and inter-state power transmission.

Based on an annual analysis, we conclude that this region can satisfy its electric power requirements while fully complying with legislated water restrictions at moderate cost by compensating the curtailment of output from some plants by otherwise unutilized capacities of other plants in the region. When we revisit the analysis using a monthly time step, however, sharp seasonal variations exhibit a strong impact on economic costs. In the summer months, intra-state transmission does not suffice, and regional demand cannot be met in the absence of substantial inter-state transmission.

Keywords: thermoelectric power production, water constraints, interregional input-output model, World Trade Model, choice of technology, scenario analysis

1. Introduction

Virtually every human activity requires water. Globally the clear majority of water withdrawals from the environment are used for crop irrigation and livestock, and the runoff of agricultural wastewater to surface and ground water is often the most important source of water pollution in a region due to its load of residues from fertilizers, pesticides, and animal wastes. Regional variation is important, however. In the United States industrial withdrawals exceed agricultural ones, and cooling in thermoelectric power plants is the largest single industrial use of water. The pollutant of concern in the discharge of wastewater from power plants is their heat content. But also recently, as emphasized by (Feeley et al., 2008) in the U.S. water availability represents a growing concern for meeting future power generation needs. The US Department of Energy's (DOE) National Energy Technology Laboratory (NETL) is engaged in a research and development (R&D) program to reduce freshwater withdrawal (total quantity of water utilized) and consumption (portion of withdrawal not returned to the source) from existing and future thermoelectric power generating facilities. The Innovations for Existing Plants (IEP) Program is currently developing to reduce water use while minimizing the impacts of plant operations on water quality.

This study focuses on the highly urbanized Northeast region of the United States, where thermoelectric plants provide most of the electric power. While the region is considered water-abundant, its power sector is nevertheless subjected to legislative constraints on water withdrawals. The U.S. Clean Water Act (CWA) of 1972 sets surface water quality standards not only on conventional pollutants and toxic substances but on thermal pollution as well (Copeland, 2010). These standards take the form of temperature constraints on freshwater withdrawals to prevent unacceptable levels of waste heat in water subsequently discharged by power plants, effectively restricting the amount of water available to them and impacting the potential output and efficiency of the plant. These standards are not strictly enforced, however, and some analysts have expressed concern that enforcement of the legislation restricting water withdrawals and discharges could not only increase the cost of power production but even compromise the ability of a region to meet effective demand for power. This study sets out to contribute to existing efforts in examining the grounds for this concern. Thermoelectric plants make use of mainly two categories of cooling technologies. In a once-though system, large amounts of water are withdrawn and, after cooling steam, discharged back to the river at a higher temperature. Power plants using this technology are responsible for the entire net increase in waste heat in the rivers in the Northeast region with substantial consequences for aquatic ecosystems (Stewart et al., 2013). The main alternative is a closed-cycle system that usually utilizes a cooling tower to dissipate heat to the atmosphere before recirculating the water for reuse in the plant. The latter system is costlier, less efficient in power production, and loses substantially more water to evaporation. However, it requires much lower water withdrawals and does not discharge heated water.

This analysis starts from a multiregional input-output modeling framework, the World Trade Model with Rectangular Choice of Technology (WTM/RCOT). The modeling framework has been applied in several studies about the use of water and characteristics of wastewater both globally and in specific regions to study the economic and resource implications of the use of water for agriculture. Now we apply the model to an existing input-output database of the 13 Northeastern states that is extended to incorporate technical data describing the thermoelectric power sector disaggregated by the fuel type and cooling system of power plants in each state. Several scenarios are analyzed to estimate the costs and resource implications of different limits imposed on the thermal pollution associated with the wastewater discharges. Contrary to their findings, our results suggest that the region can fulfill the present demand for power at moderate cost if the legislated restrictions are enforced, provided that adequate capacity exists for inter-state transmission during the summer months, which appears to be the case.

Historically an input-output analysis consisted of the application of the basic one-region model to an economic database in money values. Today multiregional input-output analysis is widely used to evaluate more detailed scenarios (see the extended discussion in Duchin et al. (in press)), and databases in mixed units increasingly incorporate data about alternative technologies and about resource stocks and flows. The present study contributes to this broadening of scope of the questions that can be addressed, and the deepening of the empirical content of input-output databases, aimed at evaluating scenarios about resource conservation and waste reduction.

Literature Review

Most studies about water scarcity using inter-regional input-output models have focused on withdrawals for crop irrigation, the largest contributor to water consumption globally and in most economies. Like our work, they rely on making use of detailed engineering data in order to make use of them in a more generalized economy wide application. Springer & Duchin (2014) use the World Trade Model (WTM) (Duchin 2005) to investigate the ability to feed the world population projected for 2050: they estimate the costs that would be imposed under alternative assumptions about restrictions on the use of arable land and fresh water and about agricultural technologies and diets in different world regions. López-Morales and Duchin (2011 and 2014) and Duchin and López-Morales (2012) apply the WTM framework to hydro-economic regions within Mexico (rather than to the global economy) to analyze the impacts on prices and the regional distribution of food production of policies that impose quantitative limits or money fees on water withdrawals for agriculture in regions where sources are currently over-exploited.

Present and future water uses for the energy sector, and more specifically for the thermoelectric sector in the U.S. have been studied in different works (Yang and Dziegielewski, 2007)(Torcellini et al., 2003)(Sovacool and Sovacool, 2009)(Newmark, 2013)(Rogers, 2012)(Vassolo and Döll, 2005). Thermoelectric plants in the U.S. withdraw even more water than agricultural establishments, although historically little of it has been consumed, and the research literature includes a number of engineering studies on the subject. Fthenakis & Kim (2010) survey the life-cycle assessment (LCA) literature as the basis for providing a full life-cycle accounting of water requirements for electricity production in the United States. They account for water used in the extraction, processing and transportation of a variety of renewable and non-renewable fuels and for the construction, operation, decommissioning and disposal of power plants. Meldrum et al. (2013) also review the relevant LCA literature and provide detailed, harmonized information on water withdrawals and consumption for electricity production, taking explicitly into account thermal efficiency, output capacity, and lifetime of power plants.

While most LCA studies are carried out at the national scale, an exception is the contribution of Cohen and Ramaswami (2014), who quantify water footprints for cities, taking account of the local conditions and mix of technologies. They analyze risks associated with constraints on transboundary water flows for power generation in 43 U.S. cities, distinguishing the effects of different technologies and government policies. Liang et al. (2011) develop a water management framework for even smaller spatial units. They construct an input-output model for an industrial park that includes a power plant to analyze alternative approaches to reducing water requirements, the volume of wastewater, and water pollution.

While Liang et al. do not consider thermal pollution, this is the focus of a study by Förster & Lilliestam (2010). These authors characterize a hypothetical nuclear power plant with once-through cooling on a hypothetical river in Central Europe and investigate how temperature rises might affect productivity under alternative assumptions about the future climate. Based on a projected increase in river temperature and decrease in river flows, they quantify the reduction in production on a daily basis using an engineering model and then apply an exogenous price to the reduction in production as an estimate of the money costs incurred.

Miara et al. (2013) also investigate the potential for thermal pollution of water to reduce the volume of power generation in individual plants, in this case in the Northeast of the U.S. They couple two existing models, the Framework for Aquatic Modeling in the Earth System (Stewart et al. 2013) and the Thermoelectric Power and Thermal Pollution Model (Miara & Vörösmarty 2013). The former model simulates operations of all 384 power plants in the region, while the latter calculates reductions in electricity generation associated with thermal pollution for each individual plant on a monthly basis. Like Cohen and Ramaswami (2014), Liang et al. (2011), and Förster and Lilliestam (2010), they take into account the spatial location of each plant in evaluating the impact on it of legislative restrictions on its withdrawals of water as well as the impact of its activities on plants downstream. Also like Förster and Lilliestam (2010), they incorporate the effects on plant productivity of the temperature of cooling water distinguished by month.

Objectives

A first objective is to further advance existing collaborations of input-output modelers with LCA analysts and modelers of specific sets of technologies by situating the operations of power plants and their use of water within an interregional input-output model. Our point of departure is mainly the concerns of the US Departments greatly summarized in (Feeley et al., 2008), and notably the work of Miara et al. (2013) because it addresses some of the questions about the effects of water restrictions in the studied region that we would like to revisit and provides much of the technical information needed to supplement the economic database. While we do not retain the full spatial detail of their models, we are able to situate the analysis within an economic framework that includes all sectors of the economy and the interactions among them, and enables interstate trade, which takes the form of power transmission in the case of the thermoelectric sector. We are also able to couple the quantitative analysis of physical relationships with the associated costs and prices, which are endogenous in our framework. We make use of the published data in that article as well as underlying plant-level detail provided by Miara (2014). Our analysis is situated at a medium spatial level, the individual state, and the temporal unit is both the year, typical for input-output studies, and the month. Of the six scenarios analyzed by Miara et al. (2013), we make use of two, the baseline and the strict enforcement of legislative regulations that does not allow a power plant to operate if the upstream water temperature exceeds specified limits.

Miara et al. make an exogenous assignment to each power plant of the amount of electricity demand it must satisfy, set equal to the actual amount generated in a particular time frame, effectively imposing it as an upper bound for the plant's output. If a plant is unable to satisfy its assignment, that shortfall is counted as a reduction in the region's output. We revisit the impact of the water restrictions on the production of power in the region by allowing for several adjustment mechanisms. One is to take account of plant capacities and allow for the inter-state transmission of power so that unused, even if costlier, capacity in one state can compensate for loss of output in plants elsewhere. The second is to recognize that each state has a mix of plants using different technologies, in particular different fuels, and that various ones may be put on line as water constraints change. It is also the case that quantities of water withdrawals vary substantially with cooling technologies, and we examine the impact of offering the choice of costlier but less water-intensive ones as an alternative to once-through methods. Finally, we can place a money value on the ecosystem service of providing cooling water by calculating the additional costs incurred when withdrawals and discharges of fresh water are impeded. Our research questions can be stated as follows:

1) What are the economic consequences for the Northeast region and the component states of imposing restrictions on water withdrawals?
2) How does constraining interstate electricity transmission affect these outcomes?
3) Does disaggregating the time step to a monthly basis affect the conclusions?

The remainder of the article is organized as follows. Section 2 describes the model, construction of the database, modeling extensions implemented for this study and scenario assumptions. The results of these scenario assumptions are analyzed in depth in Section 3. The final section discusses the outcomes and offers concluding remarks especially about methodology.

2. Methodology

2. 1. The WTM/RCOT Model

The World Trade Model (WTM) (Duchin 2005) is an inter-regional input-output model that captures the interactions of consumption and production in all regions and determines prices, regional production, and inter-regional trade subject to constraints on the availability of factors of production (built capital, labor, and resources such as water, required to produce goods and services)(Duchin, 2005) It is formulated as a linear program that minimizes total factor use, weighted by unit factor prices to satisfy given volumes of consumer demand by assigning production of each product to the relatively lowest-cost producers subject to their factor constraints. We incorporate into the WTM the Rectangular Choice of Technology (RCOT) model (Duchin and Levine 2012), which allows each region the choice among multiple technologies for producing any given output, where several of these alternative technologies may, but need not, operate simultaneously. In the present context, the model is applied to the 13 states of the Northeast, and the RCOT feature allows for electric power plants in each state to rely on different fuels and cooling technologies (see below) rather than having only a single, average input structure as in the standard input-output model. The WTM/RCOT model requires as inputs for each state, i, two matrices of intermediate inputs and of factor inputs per unit of sectoral output, A_i* and F_i*; a vector of final demand, y_i; and vectors of factor endowments in physical units and unit factor prices, f_i and π_i, respectively. A model solution provides the vector of outputs in each state, x_i*; region-wide prices of goods and services, p; and state-specific scarcity rents, r_i, that are greater than zero only for fully-utilized resources and are added to the exogenous portion of their prices (resulting in a factor price of $\pi_i + r_i$). The parameters and variables are defined in Table S1 in the Supplementary Information.

The primal model takes the following form:

$$Minimize\ Z = \sum_{i} \pi_i' F_i^* x_i^* \qquad (1)$$

subject to

$$\sum_i \ (I^* - A_i^*)\, x_i^* = \sum_i y_i, \quad \forall i \qquad (2)$$

$$F_i^* x_i^* \leq f_i, \ \forall i \qquad (3)$$

$$x_i^* \geq 0, \ \forall i. \qquad (4)$$

The dual model is explicit in the primal and can be written explicitly as:

$$Maximize\ W = p' \sum_i y_i - \sum_i r_i' f_i \,, \forall i \qquad (5)$$

subject to

$$(I^* - A_i^*)' p - {F_i^*}' r_i \leq {F_i^*}' \pi_i, \forall i \qquad (6)$$

$$p \geq 0 \qquad (7)$$

The objective function, Eq. (1), minimizes factor use, while (2) assures that production satisfies both intermediate and final demand and (3) imposes state-specific factor constraints. The dual assures that the unit price of each good does not exceed the cost of all the inputs (including a return on capital) required to produce it (5). The product prices, p, are set by the highest-cost among those that do produce, and rents, r_i, are earned by the lower-cost producers that are unable (or unwilling) to increase production due to factor constraints. The asterisk (*) indicates the existence of alternative technologies for one or more sectors. The matrices A_i* are rectangular: each sector's output is distributed to users along a single row, but the sector's input structure is represented by as many columns as it has technological options. Once the model is solved, a state's trade flows are calculated as the difference between its output and its consumption.

2. 2. Database

We compile for the 13 sub-regions (12 states and Washington D.C.) an input-output database that distinguishes 16 economic sectors with the power sector represented by several alternative technologies (see below), and three factors of production, namely built capital, labor, and water. (The sub-regions are identified in Table S2 and the sectors and technologies in Table S3 in the Supplementary Information.) State-level input-output tables for 2009 are modified from Dilekli & Duchin (2015) as the starting point for quantifying the parameter matrices and exogenous variables.

This starting database has a single sector for all utilities. We disaggregate it by creating columns of coefficients for three technologies for generating thermoelectric power from coal, natural gas, and nuclear fuels, and a residual column that represents the distribution of gas and municipal water plus the very small amount of hydroelectric and wind-based generation in the region.

Input structures for the three thermoelectric technologies are taken from the representation of the U.S. region in the EXIOPOL input-output database of the global economy (Tukker et al. 2009). We represent each fuel type by two columns of coefficients, one utilizing once-though cooling and the other, cooling towers. Thus, there are six combinations of fuel and cooling technology for thermoelectric production in each state.

It is standard in input-output matrices for all column sums (when evaluated in money values) to add to 1.0, meaning that for each dollar of receipts, a sector must lay out a dollar for inputs (including a return on capital). However, when there is a choice among alternative technologies, as there is in the RCOT model, the options by definition have not only different input structures but also, in general, different relative costs. A prevailing mix of technologies would have a column sum of 1.0, but that column is in fact a weighted average of component technologies for each of which the sum may be higher or lower than 1.0. A technically feasible but costlier option will have column coefficients greater than 1.0 and would become operational in a competitive economy, in the absence of subsidies or regulations, only if the former is constrained from increasing its production by running into a factor constraint, such as a shortage of water for cooling. A more competitive option, by contrast, will have column coefficients that sum to less than 1.0 and would have priority of production but factor limitations (on which it would earn a scarcity rent). We take the following approach to capture these differences in cost both among technologies in each state and among average costs of production in the different states.

To estimate the differences in costs associated with distinct technologies, we use the U.S. average wholesale price of electricity (Conti et al., 2013) as a point of reference and calculate the ratios relative to it of estimates for state-specific levelized costs disaggregated from electricity markets (reported in US Energy Information Administration, 2013). Cost estimates are available for four groupings of states: New England (CT, MA, ME, NH, RI and VT); states included in “ReliabilityFirst”, a multistate entity regulating electricity (DC, DE, MD, NJ, and PA); New York; and Virginia. We use the resulting ratios to adjust the columns of coefficients by state and fuel technology. We acknowledge that electricity markets do not perfectly coincide with state boundaries, however this is the best tradeoff in our case. Finally, we make use of a cooling system levelized annual cost based on estimates from Zhai & Rubin (2010) for technologies with cooling towers, augmenting in particular their capital requirements per unit of output. While the adjustments are crude, the outcomes in column totals (in money values), ranging between 0.74 for (for natural gas based plants in Virginia) to 1.19 (for natural gas based plants in New York), appear plausible.

We calibrate final demand for thermoelectric power based on thermoelectric output in each state as reported in EIA Form 923 (US Energy Information Administration, 2014) by using an application of the Input Output model where:

$$y = (I - A)x \tag{8}$$

to ensure that our modeling results are comparable to actual outputs. Relying on Miara (2014), we use the water coefficients for each technology, water availabilities (shown in Table S4); the generation capacities for each technology and the monthly data aggregated to the state level are from the same unpublished dataset. State-specific factor endowments of labor are from (Bureau of Labor Statistics, 2010), and capital endowments are taken from Dilekli & Duchin (2015).

2. 3 Scenarios

We revisit the two main scenarios for 2010 of Miara et al. (2013), which we call here Baseline and Restricted. Under Restricted, power plants may not withdraw any water if the temperature exceeds the legislated limit defined in the Clean Water Act of the United States. The water coefficients by technology and the water availability in each state differ under the two scenarios. While the temperature-based restrictions typically decrease the amount of water available for thermoelectric production, the restriction on upstream plants could increase water availability for plants located downstream. Operationally, temperature restrictions do increase efficiency of power plants, but the improvement rarely compensates for the loss of water supply.

To facilitate comparing our results with those of Miara et al. (2013), who do not consider inter-state transmission, we run both scenarios with and without allowing for inter-state flows. To restrict transmission of electric power in the WTM, we add an equation requiring that a state's power output equal the sum of its intermediate plus final demand. We did not consider the option of retrofitting once through plants with cooling towers, as the region already had plenty of capacity as discussed in the results.

The main four scenarios are as follows:

- Baseline with unlimited interstate electricity transmission

- Restricted with unlimited interstate electricity transmission
- Baseline NT: Baseline assumptions with no interstate transmission
- Restricted NT: Restricted water assumptions with no interstate transmission.

Scenario outcomes are calculated for two different temporal units. Input-output studies typically use only an annual time unit since they rely on databases that are compiled by statistical offices from censuses for a year-long accounting period. However, given the strong seasonality in demand for electric power for heating in the winter and cooling in the summer, as well as the seasonality of water temperatures which result in variation in water withdrawals as shown in the Table S5, all scenarios are run both on an average annual basis and for each of the twelve months using the water coefficients and water availabilities compiled from Miara (2014). This allows for a month-specific distribution of power production by state and by technologies.

We start from the Baseline scenario and then run the model repeatedly, incrementally decreasing the water availability until there is no feasible solution for the Northeast region even allowing for inter-state transmission. The Restricted scenario corresponds to one point along the way in terms of the percent reduction in water endowment for each state. This experiment makes it possible to estimate the increase in factor costs corresponding to the reduction in thermal pollution and to observe the corresponding shifts in power production by state and by technology.

3. Results

All four scenarios are feasible at the annual time step for the year 2010 whether water withdrawals are restricted and in the presence or absence of inter-state transmission. This means that regional demand for electric power can be satisfied under the legislated water withdrawal restrictions even in the absence of inter-state transmission. This production is just over 622 TWh, very close to the 610 TWh figure from Miara et al. (2013), the equivalent of $16.5 billion in factor costs incurred by the thermoelectricity sector due to prior calibration. Table 1 shows the increases in factor costs relative to the Baseline scenario, water withdrawals, and the percentage of power generated using cooling towers for the Baseline and Restricted scenarios, with and without inter-state transmission.

The bottom rows of the Table show the comparable results from Miara et al. (2013), who report a gross reduction in output of 83 TWh under the Restricted scenario at plants that are required to reduce their production to satisfy legislated limits on water withdrawals. We can modify this conclusion by showing that the capacity in place in each state, not to mention in other states throughout the region, can more than offset this loss -- but at a cost.

Imposing the legislated restrictions results in a substantial reduction in annual water withdrawals of 1.4 to 3.5 10^6 m^3 (between Baseline NT and Restricted NT, and between Baseline and Restricted, respectively), but requires substituting a portion of the once-through cooling infrastructure by more water-efficient but more capital-intensive cooling towers. Miara et al. (2013) estimate a far greater decline in the region's water withdrawals of 6 10^6 m^3 from the Baseline to the Restricted scenario with a higher rate of utilization of cooling towers than in our solution and find that the total demand in the region cannot be met.

The additional requirement for capital and labor associated with the cooling towers is the main reason for the increase in total factor costs when water withdrawals are restricted under our scenarios: they amount (in constant factor prices) to between \$50 million and \$180 million (between Baseline NT and Restricted NT, and between Baseline and Restricted, respectively), depending on whether inter-state power transmission is constrained.

Next, we examine the results when the availability of water under the Baseline scenario is progressively reduced. Factor costs increase, as would be expected, as does the adoption of cooling towers. Once water availability falls to about 50% of the Baseline volume, the model reports no physically feasible solution for satisfying power demand at any cost. Factor costs increase linearly up to about a 36% reduction in access to water; past this point, they rise more steeply (see Figure 1). The increasing rate of utilization of cooling towers is shown on the same graph. The Restricted scenario involves about a 20% reduction in withdrawals, well below this turning point in costs.

The costs attributable in our results to the current legislative restrictions range up to almost \$900 million, not taking future climatic changes into account. These costs are moderate relative to factor costs of the regional power sector of about \$16.5 billion. Dry cooling technologies, although they are costlier than cooling towers and further reduce the efficiency of power generation, could permit more extreme reductions in water withdrawals.

Interstate Transmission

We have seen that, when interstate transmission is allowed, the water withdrawal restrictions imposed by the U.S. Clean Water Act make it possible to satisfy the region's final demand while reducing water withdrawals by 17% provided there is an increase of 7% in the portion of output produced using cooling towers. The shifts in production by state and by fuel, as well as the cost of more cooling towers, raise production costs by \$180 million, small relative to the value of power sold in the region.

When no inter-state transmission is allowed, under Baseline NT and Restricted NT, closer to the assumptions of Miara et al. (2013) whose calculations have each power plant stand on its own, it is still possible to satisfy all regional demand with a decrease of 2% in withdrawals and an increase of 2% in production using cooling towers at an additional cost of only $51 M. However, the additional cost of providing for total regional final demand under the Baseline scenario *in the absence of inter-state transmission* relative to the Baseline with transmission is $752 M, a much larger cost than that associated with the imposition of restrictions on withdrawals.

Miara et al. find that enforcement of CWA would reduce withdrawals by a much greater rate of 21% annually with an increase of only 3.5% in power generated with cooling towers (Table 1). However, their calculations do not satisfy the entire demand for power nor do they suggest how the remaining demand would be satisfied, if at all, and no estimate of money cost is given.

The restriction of interstate transmission increases total factor costs (in constant factor prices) substantially, by between $620 and $750 million (between Restricted and Restricted NT and between Baseline and Baseline NT, respectively, as shown in Table 1). Like legislative restrictions, the absence of interstate transmission reduces water use, in this case by 2.7 to 4.8 10^6 m^3 (between Baseline and Baseline NT, and between Restricted and Restricted NT, respectively), attributable to a greater reliance on cooling tower technology which use less water. Electric power transmission across states allows for those states with unused capacity to substitute their output for the reduced, or costlier, production in other states.

State-Level Impacts

Results under increasing water restrictions starting from the Baseline water availabilities are shown in Figures 2 through 4 for the five states experiencing the greatest changes in power production (Baseline scenario power output by state is shown in Table S2). These outcomes reflect not only changes in water availability and water requirements but also differences in production capacities and cost structures. New Jersey, Maryland and Vermont are the three states experiencing the greatest reduction in power production: it is exclusively their facilities using once-through cooling that reduce their output as water restrictions are intensified; see Figure 2. Total production, using exclusively cooling towers, increases most in Pennsylvania, New Jersey, and New York, as shown in Figure 3, to offset the reductions. The combined changes in Figure 4 show that New Jersey's once-through based production decreases at a nearly constant rate with respect to the water restriction, while its cooling tower based production starts to produce when water is restricted by around 25% of the total availability in the Northeast. This is because low cost alternatives in the region have reached to a point where they are limited by the combined effects of capacity constraints and water constraints. At certain points cooling tower based production in New York and Pennsylvania cannot meet the demand anymore due to their fully utilized capacity. Since cooling tower based plants in New Jersey are the lowest cost among the not fully utilized ones in line in terms of being lowest cost, New Jersey’s production using one technology (cooling tower) increases while production using the other (once through) decreases.

As far as fuel choice is concerned, natural gas plants generate most of the electric power in the region, as under the Baseline scenario, irrespective of cooling technology or water restrictions.

Monthly Temporal Unit

We next examine the results of the monthly calculations to see if they require a change in the conclusions. Seasonality of the results is shown for the change in factor costs, the percentage decrease in water use and the percentage increase in the use of cooling towers under Restricted relative to the Baseline in Figure 5. Monthly final demand for power (in TWh) is the same under both scenarios (Restricted and Baseline scenarios with inter-state transmission allowed): it is included in the Figure (whose raw data along with two other scenarios is included in Table 5S) to show its strong seasonal variations, being greatest in the summer months with a somewhat smaller peak in the winter. Enforcing the constraints on water withdrawals would reduce intake by over 60% in the month August, with substantial reductions in other hot months as well, due in part to the increased reliance on cooling towers. The secondary peak of demand in the winter months appears to be accommodated with less disruption. The additional money costs in these summer months are substantial, amounting to \$340 million relative to the Baseline scenario. This is nearly double the additional cost of imposing withdrawal restrictions on an average annual basis, reported earlier, of \$180 million (Table 1).

In the case where no inter-state transmission is permitted, there is no feasible solution for satisfying regional demand for power in the months of July, August, or September: see Table S6, which shows detailed monthly results. Given the capacities and operating requirements of the plants in the region as represented in the model, it is not physically feasible to deliver an adequate amount of water under the restrictions imposed, even with the option of installing additional cooling towers.

In the case of the Northeast region of the U.S. as represented in our database, using an annual time step underestimates the costs of the restrictions because the unused power capacity in months of low demand in fall and especially spring cannot be utilized to provide for the surge in demand in the high season, and there are no cost savings relative to the Baseline in the months of low demand because the restrictions do not curtail water withdrawals in those periods. By contrast, in the case where no interstate transmission takes place, the analysis using an annual time step reports a feasible solution: that is because it implicitly allows for transferring water from months of high availability to months when restrictions are binding since the temporal physical constraints are absent. This is not in reality feasible, and we conclude that for economic activities that are subject to strong seasonal fluctuations in demand, or in climate-related phenomena like water availability and water temperature, analyses must use temporal units that capture the major seasonal variations. Input-output models are likely to be used to probe more deeply into questions like those posed in this study as well as studies about agricultural production and of course about climate change, where seasonal distinctions obviously require close examination.

4. Discussion and Conclusions

Our analysis suggests that the Northeast region of the United States can comply fully with legislated restrictions on water withdrawals for thermoelectric generation at moderate cost due to its vast generating capacity, provided that inter-state transmission is not impeded. In fact, production capacity in the region appears to be overbuilt. Between 2005 and 2009, more than 30% of power generating capacity was in use less than 12% of the time in New York and New England (Afridi et al., 2011). Interstate transmission capacity also appears to be adequate (Kwok, 2010). The case for imposing the conditions of the CWA on thermoelectric power plants in this region seems to be unambiguous. Of course, the ongoing need for maintenance and upgrading of the power grid, and resilience to pressures imposed by future changes in the regional climate, merit attention and may substantially change the outlook.

The World Trade Model (WTM) makes it possible to capture a large set of interdependencies, namely between consumption demand and production; among resource availability, technological choices, and money costs; and among economic activities in different places made possible through trade – power transmission in this case. Through the framework of the WTM, this study has introduced several innovations in input-output modeling.

Incorporation into the WTM of the Rectangular Choice of Technology (RCOT) allows for a choice among technologies by fuel and by cooling technology. The use of the RCOT model requires a departure from two deeply entrenched convictions about input-output models. The first limiting belief is that an input-output matrix is, by definition, square. Hopefully the demonstrated contribution of the ability to choose among alternative technologies and the ease with which it can be implemented will reduce resistance to considering rectangular coefficient matrices. The second limiting conviction is that column totals of an input-output matrix (in money values and including factor payments) must add to exactly 1.0. This belief is based on the experience of having to “balance” row sums and column sums in accounting databases in money values. It already needs to be revised when using matrices in mixed units since one can still add flows across rows in such matrices but not down the columns. However, when there is a choice among alternative technologies, it is vital to retain the information that some options will inevitably be more or less costly than others – meaning that, *ex ante*, they must be represented with column sums that (in money values) are greater than or less than 1.0. The common output will have a single price, and low-cost producers will earn scarcity rents that bring their *ex post* column sums, in money values, to 1.0. If the highest-cost producers actually produce, the price of the output will rise, and lower-cost producers will receive scarcity rents.) This innovation has been introduced first by Dilekli and Duchin (2015) and for the second time in the present study.

It is also, to our knowledge, the first time that an input-output study employs the month rather than the year as the temporal unit. This choice of unit allows the model to capture seasonal differences in demand and in environmental conditions, such as atmospheric temperature, water availability, and the heat content of water, which affect the operation of the economy, in particular in agriculture and power production. The strikingly different annual conclusions from this study when the distinctive features of the warmer months are made explicit demonstrate the importance of the choice of time unit.

We consider that these extensions to input-output models, and methods for accommodating increasingly rich descriptions of prevailing situations, can strengthen and broaden the bridges between input-output economics, process-level analysis, and other avenues for collaboration. The most fundamental contribution associated with situating the analysis within an economic framework is that the money value of ecosystem services, in this case the use of water for cooling, can be made endogenous. The standard practice for putting a money value on ecosystem services is to assign an exogenous money value to each unit of the service. This approach assumes an intrinsic value per unit of surface area for each category of ecosystem and adds the values of component ecosystems to reach an aggregate estimate, as implemented by Costanza et al. (1997 and 2014). Our approach makes it possible to make endogenous estimates of the money value of impairing ecosystems by calculating the additional costs incurred to compensate for foregoing the service, or for preventative or remedial measures. Of course, some ecosystem services are so fundamentally necessary for life on earth that it is meaningless to assign a money value to preserving them.

The current and similar analyses would benefit from increasingly deeper cross-disciplinary collaboration to achieve a fuller coupling of the engineering and economic research questions, assumptions, databases, and models. In particular, it would be valuable to evaluate the conclusions reached on the basis of this economic analysis using engineering and earth system models, iteratively if necessary, focused as they are on far more detailed attributes of individual power plants and their locations relative to river systems. This coupling would make it possible to make use of the engineering content while also capturing the interdependence of different economic activities and a regional perspective on the interdependence among spatially distributed economic activities. Another crucial future line of research is to investigate the implications of scenarios about the likely future climatic change in the Northeast, in particular changes in temperature and in precipitation patterns, in conjunction with likely socioeconomic changes.

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Tables and Figures

Table 1. Additional Cost and Water Use under Four Alternative Scenarios

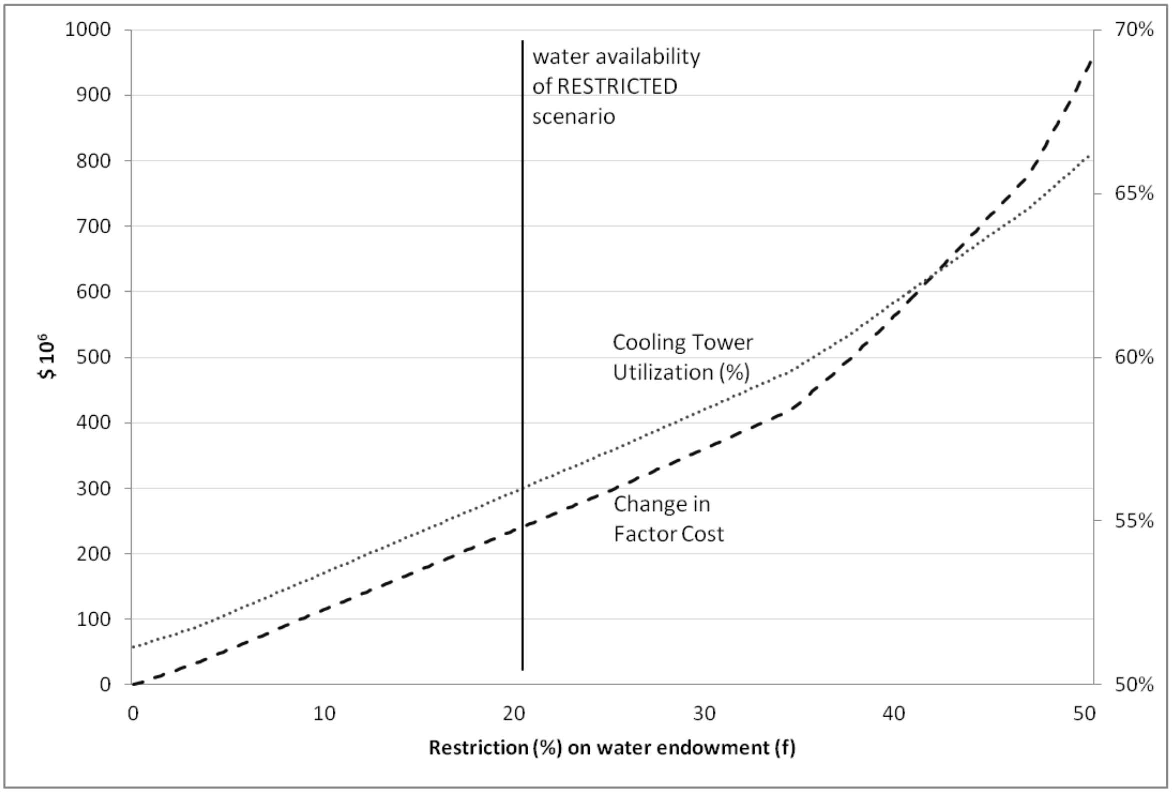
	Scenario	**Increase in factor costs ($\$10^6$)**	**Water withdrawals (10^6 m^3)**	**Cooling tower (%)**
Model Results	Baseline	0	20.9	52.5
	Restricted	181	17.4	56.0
	Baseline NT	752	16.1	56.4
	Restricted NT	803	14.7	57.4
Miara et al. (2013) Scenarios	Baseline	--	29.0	60.0
	Restricted	--	23.0	62.1

Notes:

1. See text for the definition of scenarios.
2. Increase in factor costs is relative to the Baseline scenario with inter-state transmission. It is measured in constant factor prices.
3. Cooling tower figures refer to the % of power generated using this cooling technology.

Source: Model results and Miara et al. (2013).

Figure 1. Change in Factor Costs and in Reliance on Cooling Towers with Increasing Restriction of Water Endowment

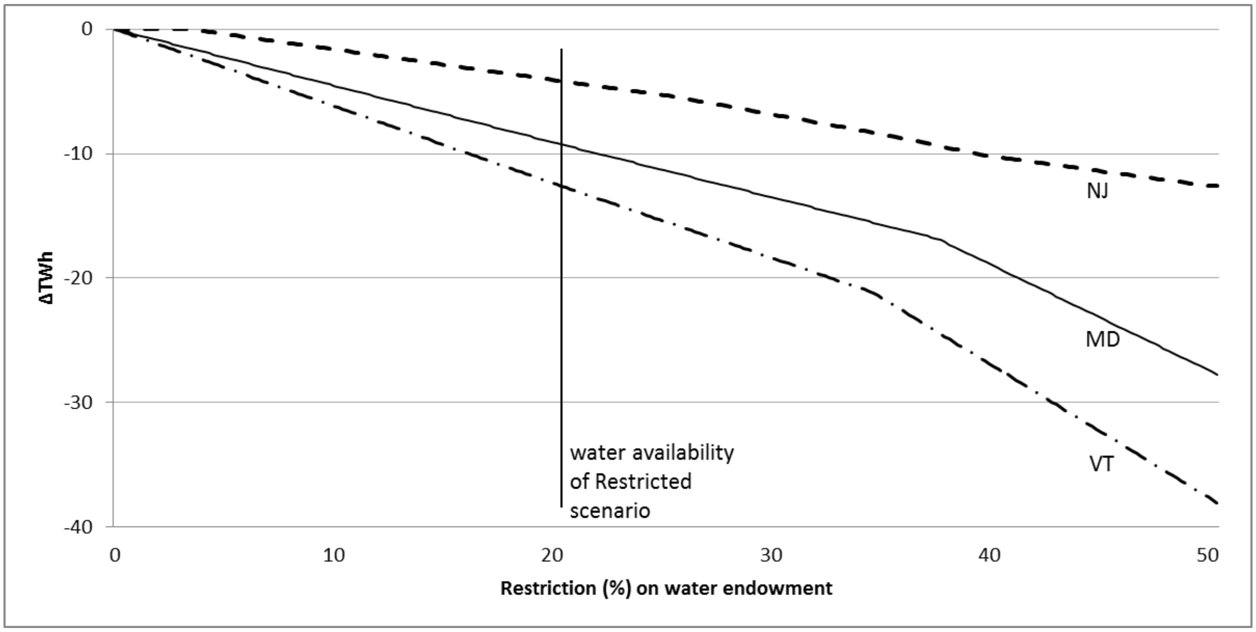


Notes:

1. Change in factor costs is relative to the Baseline costs with transmission and is measured on the left axis.
2. Cooling tower utilization measures the percent of power generated using cooling towers rather than once-through technologies; it is measured on the right axis.

Source: Model results.

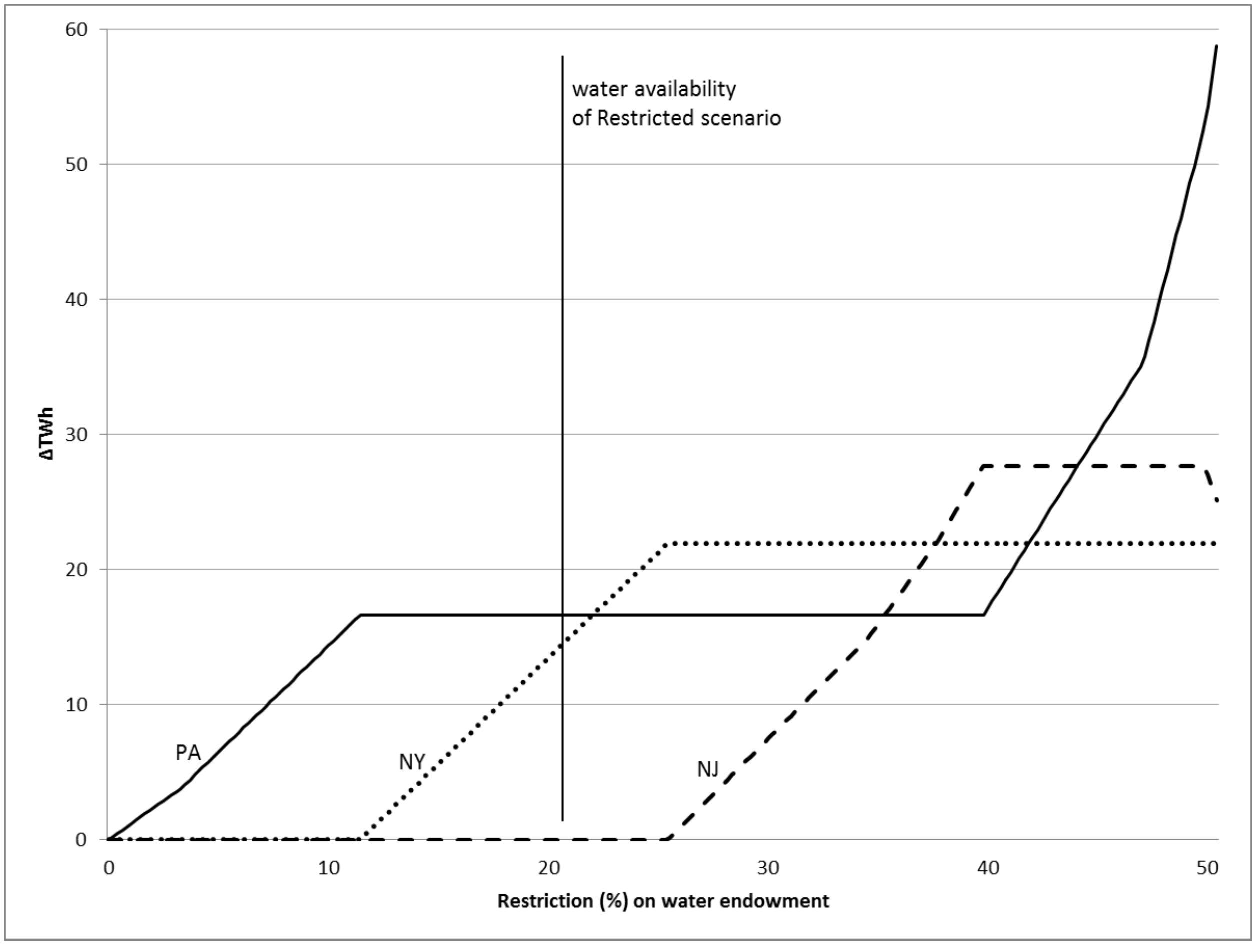
Figure 2. Reduction in Power Production using Once-Through Cooling in New Jersey, Maryland and Vermont with Increasing Restriction of Water Endowment



Note: ΔTWh refers to decline in power produced.

Source: Model results.

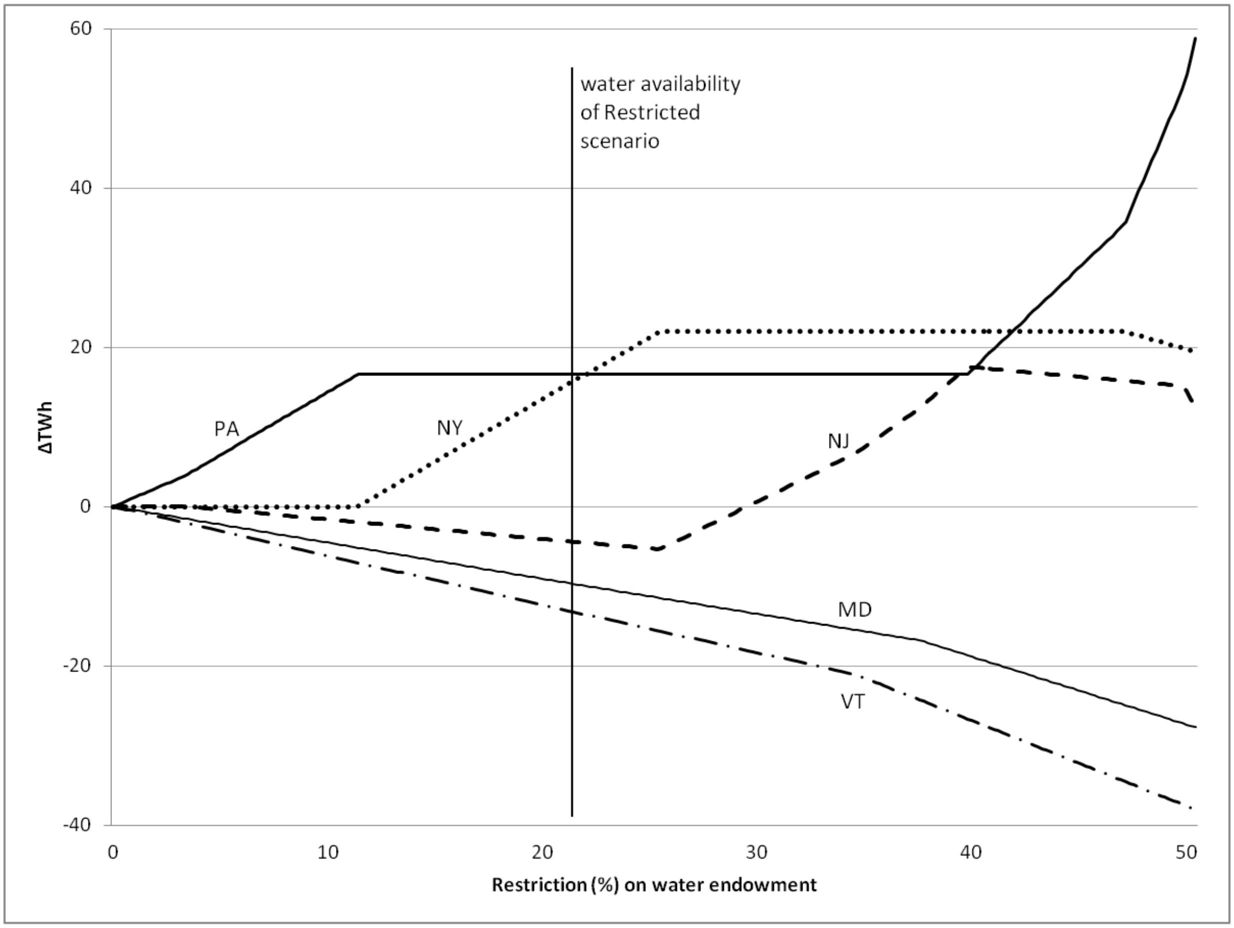
Figure 3. Increases in Power Production using Cooling Towers in Pennsylvania, New Jersey and New York with Increasing Restriction of Water Endowment



Note: ΔTWh refers to increase in power produced.

Source: Model results.

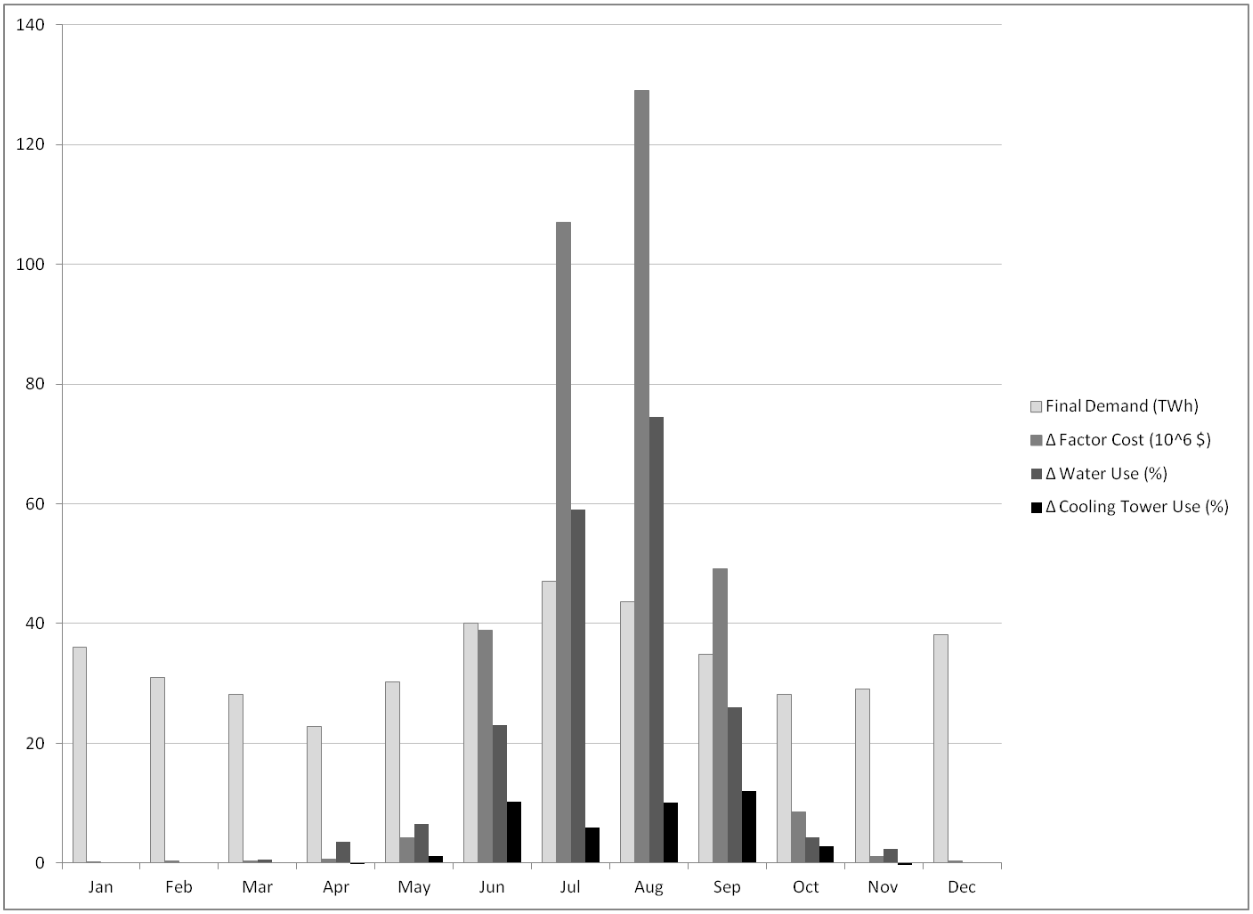
Figure 4. Changes in Total Power Production Irrespective of Cooling Technology in Five States with Increasing Restriction of Water Endowment



Note: ΔTWh refers to change in power produced.

Source: Model results.

Figure 5. Comparisons of Monthly Statistics between Baseline and Restricted Scenarios



Notes:

1. The same y-axis is used for four variables measured in three different units (energy, money, and percentage) to emphasize their seasonality.
2. Final demand (the sum of consumption, investment, government purchases, and net exports out of the region) for thermoelectric power (in TWh) is calibrated to match total output as reported in EIA Form 923 (US Energy Information Administration 2014); the latter is defined by Miara et al. (2013) as total demand for thermoelectricity.
3. Δ Factor Cost (10^6 $) refers to the increase in total factor costs under the Restricted Scenario over the Baseline results for the same month.
4. Δ Water Use (%) refers to increases in total water withdrawal under the Restricted Scenario over the Baseline results for the same month.
5. Δ Cooling Tower Use (%) refers to the percentage increase in power generated using cooling towers under the Restricted Scenario relative to the Baseline results for the same month.

Source: (US Energy Information Administration, 2014) and Model results.