

Changing the spatial location of electricity generation to increase water availability in areas with drought: a feasibility study and quantification of air quality impacts in Texas

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2013 Environ. Res. Lett. 8 035029

(<http://iopscience.iop.org/1748-9326/8/3/035029>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 18.51.1.88

This content was downloaded on 09/12/2013 at 16:03

Please note that [terms and conditions apply](#).

Changing the spatial location of electricity generation to increase water availability in areas with drought: a feasibility study and quantification of air quality impacts in Texas

Adam P Pacsi¹, Nawaf S Alhajeri¹, Mort D Webster², Michael E Webber³ and David T Allen¹

¹ Center for Energy and Environmental Resources, University of Texas at Austin, 10100 Burnet Road, Austin, TX 78758, USA

² Engineering Systems Division, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Building E40-235, Cambridge, MA 02139, USA

³ Department of Mechanical Engineering, University of Texas at Austin, 204 E. Dean Keeton Street C2200, Austin, TX 78712, USA

E-mail: allen@che.utexas.edu

Received 5 February 2013

Accepted for publication 26 July 2013


Published 20 August 2013

Online at stacks.iop.org/ERL/8/035029

Abstract

The feasibility, cost, and air quality impacts of using electrical grids to shift water use from drought-stricken regions to areas with more water availability were examined. Power plant cooling represents a large portion of freshwater withdrawals in the United States, and shifting where electricity generation occurs can allow the grid to act as a virtual water pipeline, increasing water availability in regions with drought by reducing water consumption and withdrawals for power generation. During a 2006 drought, shifting electricity generation out of the most impacted areas of South Texas (~10% of base case generation) to other parts of the grid would have been feasible using transmission and power generation available at the time, and some areas would experience changes in air quality. Although expensive, drought-based electricity dispatch is a potential parallel strategy that can be faster to implement than other infrastructure changes, such as air cooling or water pipelines.

Keywords: electricity, air quality, drought, ERCOT, consumption, withdrawals, Texas

 Online supplementary data available from stacks.iop.org/ERL/8/035029/mmedia

1. Introduction

1.1. Background

Over the past several decades, droughts in the United States have tended to become more extreme [1], and drought is

expected to become more frequent in many areas of the United States, including Texas [2]. A drought in the western United States from 1998 to 2004 was nearly record setting in terms of decreased water availability [3, 4]. Other short term droughts, such as in Texas in 2011 [5] and the Midwest in 2012 [6], have also been severe. In the United States, cooling for electricity generating units (EGUs), which are commonly known as power plants, accounts for approximately 40% of freshwater withdrawals [7], which is defined as the total amount of water that is removed from a source [8]. Power



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](http://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

plants also account for approximately 3% of total domestic water consumption [9], which is defined as the portion of water that is not returned to the source from which it was removed [10]. Due to their critical need for cooling water, thermoelectric power plants are vulnerable to water shortages that can occur during drought [11]. For example, in the summer of 2007, severe droughts in the southeastern United States forced localized reductions in nuclear power generation due to insufficient cooling water [12, 13]. Thus, drought can increase stress on both the water and electricity generation infrastructures.

Texas makes a particularly interesting testbed for examining the interconnectivity of water systems and electricity generation. From a water systems perspective, the state has large variability in precipitation from arid (west) to relatively wet (east) and several river systems that do not cross state boundaries [11]. Texas also has a self-contained electric grid, the Electric Reliability Council of Texas (ERCOT), which services 23 million customers, which is small enough to model effectively but large enough to have useful results for the national scale [14]. The generation resources in ERCOT are a reasonable approximation of the national mix and include all major fuel types and prime mover technologies (such as combined cycle, steam turbine, and simple cycle combustion turbine natural gas-fired power plants) [15]. Texas also has experienced several severe droughts in recent history [16]. Finally, future population and electricity demand growth in Texas is predicted to increase the stress on both the water and electricity infrastructures systems [7, 17], even during times with relatively more water availability.

1.2. Scope of work

Previous studies [14, 18] have shown that changes in where electricity is generated can cause significant changes in both the magnitude and location of air pollutant emissions. Electricity generation can be dispatched, where dispatching refers to the process by which power plants are assigned generation by an electric grid operator like ERCOT, to minimize air quality impacts if the electric grid has sufficient flexibility in transmission and generation capacity. This work expands on these previous analyses of dispatching for air quality objectives, demonstrating that the grid can also be operated as a virtual water 'pipeline' to 'deliver' increased water availability in drought-stricken regions by shifting power generation to other areas of the grid. These shifts in generation, while increasing water availability in targeted regions, can potentially increase electricity costs and change the spatial distribution of air pollutant emissions. Individual power plant factors such as fuel type [19, 20], cooling system configuration [7, 20] and prime movers (e.g. the power cycle) can affect water withdrawals and water consumption. Thus, changing the dispatch order may also impact the fuel mix for ERCOT, which can affect water usage in the electricity generation sector. Typical values for fossil fuels EGUs range from 1100 to 189 000 l MWh⁻¹ for water withdrawals and 1000–1800 l MWh⁻¹ for water consumption [7]. This work reports changes to both consumptive water use and

withdrawals at power plants in Texas that would result from dispatching power generation away from drought-stricken regions.

Recent studies [21–23] have examined reducing the water footprint of electricity generation through the installation of air cooling technologies, which take years to deploy. Since the dispatch order can be adjusted on a daily or even faster basis, the approach outlined in this work offers the potential for rapid implementation and quick adaptation to shifts in the location of drought. The shifts may also have non-monetized costs associated with changes in the amount and location of emissions of nitrogen oxides (NO_x) and sulfur dioxide (SO₂). NO_x is a precursor for ozone formation, which has been linked to health impacts such as increased respiratory mortality [24, 25]. While SO₂ is one of many precursors for fine particulate matter (PM), it contributes to the formation of PM sulfate, which is the largest mass component of fine PM in Texas [26], and the most sensitive PM species to changes in electricity generation [27, 28]. Fine PM has been shown to increase instances of lung cancer and overall morbidity [24, 29].

2. Methods

2.1. Episode selection

For this work, the potential impacts of drought-based electricity dispatch in ERCOT were examined using a 33-day episode from 31 May–2 July 2006. While Texas has experienced several periods of drought in the last decade [16], this particular drought episode was chosen for this proof of concept work since it corresponded with the period that the Texas Commission on Environmental Quality (TCEQ) had previously chosen for air quality planning in Texas [30]. In Texas, both the Dallas–Fort Worth and Houston areas are currently in non-compliance with the federal 8-h ozone standard [31], and policy changes that would negatively impact air quality in these areas would thus be difficult to implement. Therefore, it is important to characterize the potential air quality impacts of water availability-based changes in the electricity generation sector. A description of the air quality model used in this work is available in the supplementary data (available at stacks.iop.org/ERL/8/035029/mmedia).

2.2. Power plant water use factors

The average water use per unit of generation at each power plant in ERCOT was characterized by a previously-developed consumption rate [10] and withdrawal rate [9]. These data were used, rather than data from the US Energy Information Administration (EIA) [32] because recent research [9, 20] has found numerous inaccuracies in water withdrawal data that is reported annually to the EIA. For the year 2008, Averyt *et al* [9] classified each power plant in the United States based on its fuel, generation technology, and cooling system type and assigned the median withdrawal rate for the configuration [20]. Power plant-specific consumption rates

Table 1. Summary of the drought-driven constraints on electricity generation for each scenario examined in this study.

Scenario name	Constraints in abnormally dry and moderate drought regions	Constraints in severe drought regions	Changes in extreme and exceptional drought regions
Base case	None	None	None
A	None	None	No water withdrawing electricity generation
B	None	0% net consumptive water increase from the base case	No water withdrawing electricity generation
C	None	5% net consumptive water decrease from the base case	No water withdrawing electricity generation
D	None	10% net consumptive water decrease from the base case	No water withdrawing electricity generation

were estimated by King *et al* [10] using 2006 total water consumption data and total electricity generation that was reported to the TCEQ. King *et al* [10] screened data for completeness and used average factors specific to fuel type and generation technology when incomplete or erroneous data was found. Both resources [9, 10] provide estimates of the error bounds associated these factors, but a detailed discussion of error bounds is beyond the scope of this work.

2.3. Electricity generation model

For each hour in the episode, a PowerWorld model was used to determine the generation level (MWh) at each power plant in ERCOT that minimized the total cost of electricity generation subject to meeting demand and including line losses, transmission line capacity limits, and EGU maximum and minimum generation levels. A linear programming (LP) approach was used that allowed for all constraints to be met, including inequalities. More information on the implementation of this electricity generation model in ERCOT is available in prior publications [14, 33]. As shown in table S1 (see supplementary data available at stacks.iop.org/ERL/8/035029/mmedia), the PowerWorld model was validated based on a comparison to industry data for June 2006 [32], and performance was consistent with a similar model in peer-reviewed literature [34]. For each hour and each power plant, water consumption and withdrawals were calculated by multiplying the unit generation (MWh) by the matched water usage rates ($m^3 MWh^{-1}$) that were described in section 1.2.

For the base case in this work, the PowerWorld model was executed with an objective of minimizing the total generation cost in ERCOT while excluding water-based constraints. The choice of a cost-minimized base case is consistent with ERCOT operations in which generation rights are assigned based on bidding by power plants while accounting for transmission and security constraints [35]. In addition, four scenarios in which the grid was operated based on water consumption constraints were examined and are summarized in table 1. The water consumption constraints applied to ERCOT were based on the spatial location of each power

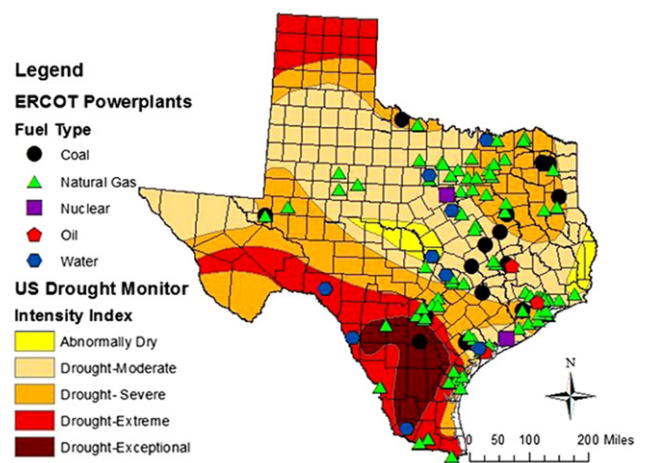


Figure 1. Location of ERCOT power plants requiring cooling water withdrawals and US Drought Monitor intensity index for 13 June 2006 [36]. Drought intensity increases from abnormally dry (yellow) to drought-exceptional (dark red). Almost 10% of ERCOT base-load generating capacity was located in south Texas locations under extreme or exceptional drought.

plant relative to the US Drought Monitor intensity index for Texas on 13 June 2006 [36], as shown in figure 1. For this period, all of Texas was classified as being under drought conditions [36], although the intensity varied geographically from abnormally dry (least intense) to exceptional drought (most intense) as shown in figure 1. In practice, drought-based changes to the spatial location of electricity generation in Texas could be applied based on a number of different drought measurement techniques, but this work presents a proof of concept using the US Drought Monitor intensity index.

The first scenario (Scenario A) involved eliminating water withdrawing electricity generation in areas of South Texas with extreme and exceptional drought (as shown in figure 1) and represented the minimum cost strategy for shifting water use from the highest drought areas. For Scenario A, the shifted electricity generation (7.7 GW of generation capacity and 9.9% of base case generation) was dispatched based on minimizing total additional cost in ERCOT. In order to prevent exporting water availability issues

to other areas that were classified as having severe drought (the next most intense drought class as show figure 1), three additional scenarios were modeled in which no generation occurred in extreme and exceptional drought regions (the same constraint as Scenario A) and with another constraint that total cooling water consumption in severe drought areas either remained constant (Scenario B), decreased by 5% (Scenario C), or decreased by 10% (Scenario D) compared to the base case. The net consumptive water constraints in severe drought regions (Scenarios B–D) were enforced by reducing the maximum generation at each power plant in the region by a constant factor until the constraint was met. For example, in Scenario C, the maximum generation at all power plants in the severe drought region were reduced by 37% so that the sum of all water consumption in the severe drought region was 5% less than in the base case simulation. While more sophisticated approaches to reducing cooling water consumption in severe drought regions could be implemented in future work, the constant factor approach was chosen for its clarity as a proof of concept. Further reductions in water consumption (>10%) in severe drought regions violated capacity or transmission constraints within ERCOT. This work also reports changes to water withdrawals, which were not used to constrain grid operation. Using this 2006 episode, the results presented here are a first attempt at assessing the feasibility and relative cost of this strategy, rather than a full-scale implementation model.

3. Results and discussions

3.1. Drought-based grid changes and costs

All scenarios offered an average reduction of consumptive water use of $188\,000\text{ m}^3\text{ d}^{-1}$ and withdrawal reductions of $1\,740\,000\text{ m}^3\text{ d}^{-1}$ in areas with extreme and exceptional drought (tables S2 and S3 in supplementary data available at stacks.iop.org/ERL/8/035029/mmedia). The avoided water consumption in extreme and exceptional drought regions would be enough for the personal use of 360 000 people based on average domestic water usage in Texas [8], for the production of ethanol for 1.8 million miles of driving from corn grain in irrigated fields [37], or to produce 16 billion cubic feet per day of the average Texas shale gas [19]. For Scenario D, in which water consumption in the severe drought region is reduced by 10% from the base case, the electric grid offers enough flexibility to avoid additional water consumption of $47\,000\text{ m}^3\text{ d}^{-1}$ in the regions with severe drought in this episode. While cooling water consumption in the rest of ERCOT (abnormally dry and moderate drought regions as shown in figure 1) increases by 10%–34% for the four scenarios (A–D) compared to the base case, total cooling water consumption in ERCOT (table S2) decreases in all scenarios compared to the base case. The maximum of 7% reduction in total ERCOT cooling water consumption occurs in Scenario A, in which electricity dispatch is unconstrained in the severe drought regions. The reduction in cooling water consumption in Scenario A is driven by decreased coal-fired electricity generation in

ERCOT (table S4, see supplementary data available at stacks.iop.org/ERL/8/035029/mmedia), which typically has a higher water consumption rate than the natural gas facilities [19, 23] that our model indicates would replace the coal-fired generation. The total savings in cooling water consumption are reduced with increasing constraints in the severe drought region due to the increased use of less efficient peaking natural gas plants in ERCOT. Total water withdrawals increase 5%–23% in ERCOT versus the base case scenario (table S3) and increase with increasing grid constraints. The increases in ERCOT total cooling water withdrawals are driven by more use of less efficient natural gas plants, which often have once-through cooling water systems in Texas.

The shifting of 9.9% of the ERCOT episode base case generation from EGUs in areas of extreme and exceptional drought in South Texas causes electricity generation to become more expensive by dispatching generation to higher cost power plants in other locations. Scenario A would increase the average cost of electricity generation by $\$1.28\text{ MWh}^{-1}$, a 5% increase over the base case scenario. Further restricting water consumption in severe drought regions (Scenarios B–D), as shown in table S5 (see supplementary data available at stacks.iop.org/ERL/8/035029/mmedia), would increase the average ERCOT generation cost per MWh by up to 13%. While average prices can illustrate the magnitude of the cost associated with a change, electricity is priced based on marginal cost, which varies with demand level. In this episode, cost increases associated with drought-based electricity dispatch in ERCOT were modeled to range from $\$0.51$ to $\$0.83\text{ MWh}^{-1}$ for base-load conditions (2%–3% increase from the base case) and $\$3$ to $\$15\text{ MWh}^{-1}$ (9%–45% increase from the base case) for the episode peak demand hour.

Past research has characterized the cost of changing the electricity dispatch for ERCOT based on NO_x emissions pricing [14] and fuel costs [33, 34]. This work characterizes the range of price incentives ($\text{\$ MWh}^{-1}$) that would need to be given to electricity producers in less drought-affected regions of ERCOT in order to shift generation to some of the more expensive facilities in those areas. In practice, these price incentives could either be given as a subsidy to facilities at which more generation is desired or as an additional cost to facilities in drought-stricken regions in order to change the relative dispatch order in ERCOT. However, this strategy might have additional costs associated with compensating EGUs that would be forced to eliminate or decrease generation, but estimating these costs is beyond the scope of this work. In addition, the change from a zonal to a nodal based pricing system, undertaken by ERCOT in 2010 to improve dispatch efficiencies and price signals [35] may alter costs.

Recently, Texas has built physical pipelines as a method of increasing water availability in some regions with prolonged water scarcity concerns. For example, a planned 240 mile pipeline to deliver $370\,000\text{ m}^3\text{ d}^{-1}$ from Lake Palestine to the Dallas–Fort Worth area would have a total capital cost of $\$888$ million and an estimated cost of $\$0.63\text{ m}^{-3}$ water [38]. If a similar pipeline were

constructed to deliver water for the power generation sector in a region and was used only during drought years, the unit cost would double to $\$1.26 \text{ m}^{-3}$ water, assuming the frequency of drought in Texas remained the same as from 1990 to 2010 [16]. By comparison, the drought-based dispatch strategies would cost $\$6.80\text{--}\15.89 m^{-3} water for consumptive water reductions in extreme, exceptional, and severe drought regions and $\$0.74\text{--}\2.15 m^{-3} water for targeted withdrawal reductions in extreme and exceptional drought regions.

Another proposed policy for cooling water reductions would be to install air cooling systems at the 38 EGUs in areas of extreme and exceptional drought in this episode. The cost of air cooling is largely driven by the parasitic loss of electricity generation at the power plant caused by the technology. Assuming an average 2% parasitic loss [22], the estimated range of the cost of this air cooling strategy was found to be $\$0.09\text{--}\0.43 MWh^{-1} for the episode average and maximum electricity price, respectively, in the ERCOT South Zone [39] based on methods in Stillwell and Webber [21]. Parasitic losses can vary from nearly 0% to 10% based on factors such as temperature and humidity [21]. At the upper limit of 10% for parasitic loss, the cost of air cooling would be $\$0.37 \text{ MWh}^{-1}$ and $\$68.11 \text{ MWh}^{-1}$, at the episode average and maximum electricity price in the South Zone, respectively. While the cost of drought-based grid dispatching appears to be substantially more than air cooling with the exception of cases of high parasitic loss or electricity cost, the strategy could be implemented without making new capital investments at power plants and could respond to changes in the spatial extent of drought. Cost comparisons for drought-based dispatching and other infrastructure changes are summarized in table S6 (see supplementary data available at stacks.iop.org/ERL/8/035029/mmedia). This policy could be rapidly deployed while other physical adjustments—such as adding air cooling systems, building or expanding reservoirs, or building water pipelines—are conducted in parallel. However, it is possible that optimization in future work could improve the economics of drought-based dispatching.

3.2. Effect on regional air quality

Changing the spatial distribution of power generation in ERCOT would not only change the location of cooling water usage but also the location of air pollutant emissions in the power generation sector. Total SO_2 emissions from ERCOT power plants (as shown in table S7, see supplementary data available at stacks.iop.org/ERL/8/035029/mmedia) decrease 3–21% from the base case. In Scenario A, the reduction in SO_2 occurs because the generation from several coal EGUs in South Texas is replaced with a less sulfur-intensive power generation mix (table S4). In Scenarios B–D, additional SO_2 reductions are modeled based on decreased coal-fired power generation in the severe drought region. However, other areas (abnormally dry and moderate drought regions as shown in figure 1) experience 5–13% increases in SO_2 emissions compared to the base case (table S7,

see supplementary data available at stacks.iop.org/ERL/8/035029/mmedia). The impact on total ERCOT NO_x emissions (table S8, see supplementary data available at stacks.iop.org/ERL/8/035029/mmedia) was more complicated than for SO_2 emissions, with changes from the base case ranging from -2% (Scenario A) to $+8\%$ (Scenario D). In Scenarios B–D, NO_x emissions reductions in exceptional and extreme drought regions from decreased coal-fired power generation (table S4) were offset by the increased use of higher emitting natural gas peaking units as constraints on where generation could occur the grid were increased.

Since the secondary formation of ozone [40, 41] and PM [42] can vary significantly based on geographic location of changes in precursor emissions, photochemical modeling was used to resolve the average PM and ozone concentration changes over the episode (figures S2 and S3, see supplementary data available at stacks.iop.org/ERL/8/035029/mmedia). The maximum of the episode average changes from the base case for ozone were $+0.2$ ppb (increase from the base case) to -0.55 ppb (decrease from the base case). Maximum changes in fine PM were highly localized and on the order of $\pm 0.25 \mu\text{g m}^{-3}$. A surprising result (figure S3) was the maximum changes for fine PM that occurred in the Scenario A in the region northwest of Houston. This maximum increase was driven by locally increased generation at a facility with multiple EGUs. This area of increased PM formation was limited in Scenario B–D since generation was restricted at that facility.

4. Conclusions

The electric grid in Texas (ERCOT) can be used as a means of changing the spatial distribution of cooling water consumption and withdrawals in the state. This method was demonstrated with a model for an historical episode from 2006 in which 7.7 GW of generation capacity were in intensive drought regions were removed from the dispatch order. The approach demonstrated here would reduce cooling water consumption by $188\,000 \text{ m}^3 \text{ d}^{-1}$ in the worst-hit drought areas, which is enough water for the average daily water use of 360 000 Texans. In addition, this strategy decreased over all cooling water consumption in the state at a price that is cost competitive with air cooling at the upper end of observed electricity prices in the region, and could be a potential parallel strategy while other physical adjustment to water infrastructures are completed.

Acknowledgments

The authors thank the National Science Foundation and its Emerging Frontiers in Research and Innovation (EFRI) program for funding this research (Grant Number 0835414). Additional support was provided by the US Department of Energy. The authors declared no competing financial conflicts of interest.

References

- [1] Dai A, Trenberth K E and Qian T 2004 A global dataset of Palmer drought severity index for 1870–2002: relationship with soil moisture and effects of surface warming *J. Hydrometeorol.* **5** 1117
- [2] Strzepek K, Yohe G, Neumann J and Boehlert B 2010 Characterizing changes in drought risk for the United States from climate change *Environ. Res. Lett.* **5** 044012
- [3] Andreadis K M, Clark E A, Wood A W, Hamlet A F and Lettenmaier D P 2005 Twentieth-century drought in the conterminous United States *J. Hydrometeorol.* **6** 985
- [4] Cook E R, Seager R, Cane M A and Stahle D W 2007 North American drought: reconstructions, causes, and consequences *Earth-Sci. Rev.* **81** 93
- [5] Nielsen-Gammon J W 2012 The 2011 Texas drought *Texas Water J.* **3** 59
- [6] Schnoor J L 2012 The US drought of 2012 *Environ. Sci. Technol.* **46** 10480
- [7] King C W, Holman A S and Webber M E 2008 Thirst for energy *Nature Geosci.* **1** 283
- [8] US Geological Survey 2009 *Estimated Use of Water in the United States in 2005* (<http://pubs.usgs.gov/circ/1344/pdf/c1344.pdf>)
- [9] Averyt K, Macknick J, Rogers J, Madden N, Fisher J, Meldrum J and Newmark R 2013 Water use in electricity in the United States: an analysis of reported and calculated water use information for 2008 *Environ. Res. Lett.* **8** 015001
- [10] King C W, Duncan I and Webber M E 2008 *Water Demand Projections for Power Generation in Texas* (www.twdb.state.tx.us/publications/reports/contracted_reports/doc/0704830756ThermoelectricWaterProjection.pdf)
- [11] Stillwell A S, Clayton M E and Webber M E 2011 Technical analysis of a river basin-based model of advanced power plant cooling technologies for mitigating water management challenges *Environ. Res. Lett.* **6** 034015
- [12] Hightower M and Pierce S A 2008 The energy challenge *Nature* **452** 285
- [13] Manuel J 2008 Drought in the Southeast: lessons for water management *Environ. Health Perspect.* **116** A168
- [14] Alhajeri N S, Donohoo P, Stillwell A S, King C W, Webster M D, Webber M E and Allen D T 2011 Using market-based dispatching with environmental prices signals to reduce emissions and water use at power plants in the Texas grid *Environ. Res. Lett.* **6** 044018
- [15] Stillwell A S, King C W, Webber M E, Duncan I J and Hardberger A 2011 The energy–water nexus in Texas *Ecol. Soc.* **16** 2
- [16] National Climatic Data Center 2013 *Texas Palmer Drought Severity Index (PDSI)* (www.ncdc.noaa.gov/temp-and-precip/time-series/)
- [17] Sovacool B K and Sovacool K E 2009 Identifying future electricity–water trade-offs in the United States *Energy Policy* **37** 2763
- [18] Sun L, Webster M, McGaughey G, McDonald-Buller E C, Thompson T, Prinn R, Ellerman A D and Allen D T 2012 Flexible NO_x abatement from power plants in the eastern United States *Environ. Sci. Technol.* **46** 5607
- [19] Grubert E A, Beach F C and Webber M E 2012 Can switching fuels save water? A life cycle quantification of freshwater consumption for Texas coal and natural gas-fired electricity *Environ. Res. Lett.* **7** 045801
- [20] Macknick J, Newmark R, Heath G and Hallett K C 2012 Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature *Environ. Res. Lett.* **7** 045802
- [21] Stillwell A S and Webber M E 2013 Novel methodology for evaluating economic feasibility of low-water cooling technology retrofits at power plants *Water Policy* **15** 292
- [22] Zhai H and Rubin E S 2010 Performance and cost of wet and dry cooling systems for pulverized coal powerplants with and without carbon capture and storage *Energy Policy* **38** 5653
- [23] Feely T J, Skone T J, Stiegel G J, McNemar A, Nemeth M, Schimmoller B, Murphy J T and Manfredo L 2010 Water: a critical resource in the thermoelectric power industry *Energy* **33** 1
- [24] Anenberg S C, Horowitz L W, Tong D Q and West J J 2010 An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling *Environ. Health Perspect.* **118** 1189
- [25] Bell M I, McDermott A, Zeger S I, Samet J M and Dominici F 2004 Ozone and short-term mortality in 95 urban communities, 1987–2000 *J. Am. Med. Assoc.* **292** 2572
- [26] Russell M, Allen D T, Collins D R and Fraser M P 2004 Daily, seasonal, and spatial trends in PM_{2.5} mass and composition in southeast Texas *Aerosol Sci. Technol.* **38** 14
- [27] Mueller S F, Bailey E M and Kelsoe J J 2004 Geographic sensitivity of fine particle mass to emissions of SO₂ and NO_x *Environ. Sci. Technol.* **38** 570
- [28] Bergin M S, Shih J S, Krupnick A J, Boylan J W, Wilkinson J G, Odman M T and Russell A G 2007 Regional air quality: local and interstate impacts of NO_x and SO₂ emissions on ozone and fine particulate matter in the eastern United States *Environ. Sci. Technol.* **41** 4677
- [29] Pope C A, Burnett R T, Thun M J, Calle E E, Krewski D, Ito K and Thurston G D 2002 Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution *J. Am. Med. Assoc.* **287** 2123
- [30] Texas Commission on Environmental Quality 2010 *Dallas–Fort Worth Attainment Demonstration State Implementation Plan Revision for the 1997 Eight-Hour Ozone Standard* (www.tceq.texas.gov/airquality/sip/dfw_revisions.html)
- [31] US Environmental Protection Agency 2012 *2008 Ground-Level Ozone Standards—Region 6 Final Designations* (www.epa.gov/airquality/ozonepollution/designations/2008standards/final/region6f.htm)
- [32] US Energy Information Administration 2013 *Form EIA-923 Detailed Data* (www.eia.gov/electricity/data/eia923/)
- [33] Pacsi A P, Alhajeri N S, Zavala-Araiza D, Webster M D and Allen D T 2013 Regional air quality impacts of increased natural gas production and use in Texas *Environ. Sci. Technol.* **47** 3521
- [34] Venkatesh A, Jaramillo P, Griffin W M and Matthews H S 2012 Implications of changing natural gas prices in the United States electricity sector for SO₂, NO_x, and life cycle GHG emissions *Environ. Res. Lett.* **7** 034018
- [35] Daneshi H and Srivastava A K 2011 ERCOT electricity market: transition from zonal to nodal market operation *2011 IEEE Power and Energy Society General Mtg (San Diego, CA, 24–29 July 2011)* pp 1–7 (doi:10.1109/PES.2011.6039830)
- [36] The National Drought Mitigation Center *Drought Monitor Archives for June 13, 2006* (<http://droughtmonitor.unl.edu/archive.html>)
- [37] King C W and Webber M E 2008 Water intensity of transportation *Environ. Sci. Technol.* **42** 7866

- [38] Texas Water Development Board 2012 *2012 Water for Texas* (www.twdb.state.tx.us/publications/state_water_plan/2012/2012_SWP.pdf)
- [39] Electricity Reliability Council of Texas 2006 *Balancing Energy Services Daily Report Archive* (www.ercot.com/mktinfo/services/bal/2006/index)
- [40] Nobel C E, McDonald-Buller E C, Kimura Y and Allen D T 2001 Accounting for spatial variation of ozone productivity in NO_x emission trading *Environ. Sci. Technol.* **35** 4397
- [41] Mauzerall D L, Sultan B, Kim N and Bradford D F 2005 NO_x emissions from large point sources: variability in ozone production, resulting health damages, and economic costs *Atmos. Environ.* **39** 2851
- [42] Brock C A *et al* 2002 Particle growth in the plumes of coal-fired power plants *J. Geophys. Res.* **107** 4155