Shale Gas Availability, CO_2 Emissions, Electricity Generation Mix and Power Sector Water Use: EMF 31 Scenarios Results for the U.S.

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See footnotes at end of text.

The U.S. electricity sector is responsible for 38% of energy-related CO_2 emissions and for 45% of total water withdrawals for power plant cooling[1]. Depending on the electricity generation mix to meet future demand, power sector water usage could be enlarged or reduced. Within the past decade, coal power plants were the dominant source of electricity generation in the U.S. and in 2008 coal plants accounted for 67% of water withdrawals and 65% of consumption for thermoelectric power plants[2]. Natural gas power plants are less water intensive: for the same year, gas plants accounted for 4% of power plant freshwater withdrawals and 9% of consumption[3]. Nuclear reactors, however, require more water to produce the same amount of electricity than fossil plants with an equivalent cooling system as they are thermodynamically less efficient: in 2008, nuclear power plants produced 21% of the freshwater-cooled electricity, but accounted for 27% of all power plant freshwater withdrawals, and 24 % of consumption[4]. The water intensity of renewable energy technologies varies: some concentrating solar power plants consume more water per unit of electricity than the average coal plant, while wind farms use basically no water. Geothermal and biomass power plants also have water intensities in the range of nuclear or coal.

Nuclear and coal, on average, are the most water-intensive thermoelectric power plants. Carbon capture and storage (CCS) escalates the amount of water used if CO_2 is captured through absorption with amine solvents[5]. Furthermore, the additional power used to capture and sequester CO_2 lowers the plant's output, thus raising the amount of water used per unit of energy generated. Changes in water use from electricity generation is vulnerable to weather variability and, in turn, changes in water consumption for electricity generation affect the availability of water in other sectors of the economy. Taking into account challenges to U.S. electric power reliability, it is crucial to understand how future energy and carbon mitigation policies could impact electricity generation water usage.

We explored the relationship between shale gas availability, CO_2 reduction policies and water use in the electric power sector. We applied a multiregional MARKAL model and the publicly available EPAUS9r2014 database[6]. The original EPAUS9r2014 database was modified in line with the Energy Modeling Forum 31 (EMF 31) scenarios: EMF Reference or Baseline (Reference); High U.S. Shale Resources (High Shale); Low U.S. Shale Resources (Low Shale); Technology Performance Standard (TPS)[7]; TPS with Low Shale Resources (TPS Low) and Modeler Choice[8]. Our Modeler Choice scenario is TPS that includes additional costs for water withdrawal treatment and an upper bound on water consumption (TPS Water Constraints). We assumed that future additional water withdrawal treatment costs start in 2020 at $0.05/kgal. We estimated an upper bound on power sector water consumption by each region assuming a 35% reduction by 2050 at the national level and with different rates of water consumption decrease in different regions that are based on mean absolute percentage deviation of "Counties At-Risk" in the particular region[9].

CO_2 EMISSIONS MODELING RESULTS

In 2007–2013 U.S. electricity generation CO_2 emissions have fallen more than 15%, while system-wide CO_2 emissions have decreased only by 10% (Figure 1). Although CO_2 reduction could be assigned to the economic downturn, the continuing decline after 2010 suggests that increased availability of natural gas, and the transition from coal to natural gas has also contributed to the CO_2 decline. This trend continues in the short-term future in all scenarios since natural gas continues to replace coal-fired plants. By 2020 electricity generation CO_2 emissions are 20% below 2005 level in the Reference scenario, 27% in High Shale, 16% in Low Shale and 40% in TPS scenarios. After 2020-2025 power sector CO_2 emissions increase and are only 7%-15% below 2005 by 2050 in the scenarios without CO_2 constraints. In TPS scenarios CO_2 emissions are 48% below 2005 levels in 2050.

Total energy system CO_2 emissions are 12% below 2005 levels by 2020 and increase afterwards in the Reference scenario. By 2025, CO_2 emissions in the High Shale scenario are 15 % lower than 2005. The Low Shale scenario shows the lowest CO_2 reduction in the short-term (11% by 2020). Total system-wide CO_2 emissions in the Reference and Low Shale scenarios have a similar trend: decrease in 2005-2025,

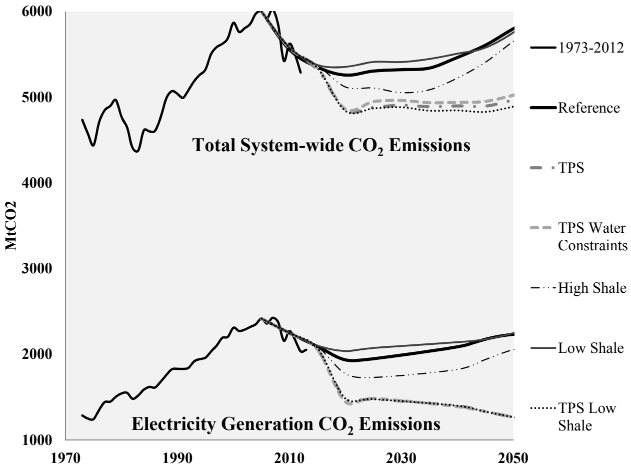

Figure 1. Total CO_2 Emissions and Electricity Generation CO_2 Emissions: Historical and Projections

stabilization in 2025-2040 and increase afterwards up to 2005 level by 2050. In the High Shale scenario natural gas supply affects CO_2 only in the short and medium-term and total CO_2 emissions by 2050 are merely 2% lower than in the Reference scenario. In TPS scenarios CO_2 emissions are only 16-18% lower than in the Reference case by 2050. Thus, the level of CO_2 abatement in electricity generation sector is higher than total energy system CO_2 abatement; so as long as there are no CO_2 constraints in other sectors, the model expands only electricity CO_2 reductions.

ELECTRICITY GENERATION MIX MODELING RESULTS

In 2005, coal provided 46%, nuclear power around 19%, natural gas nearly 20% of all electricity. Renewables (including solar, wind and large hydro) about 12%. Natural gas has been a strong competitor for power generation since 2006. In 2012, coal power plants produced a little more than 39% of all electricity, down from 46% in 2005[10]. In 2005-2050 electricity generation grows annually by 0.6% in the Reference scenario. The highest growth rates of electricity generation (1% annually) can be observed only in the High Shale scenario (Figure 2). All other scenarios show electricity generation lower than in the Reference scenario (the lowest level can be observed in TPS scenarios with annual growth rates of 0.4%). The low electricity demand in the TPS scenarios is a result of efficiency improvements and switching from electricity to other fuels. In addition, electricity co-production in industrial CHPs is higher in the scenarios with CO_2 constraints in the electricity generation sector because those emission sources are not covered by the modeled policy.

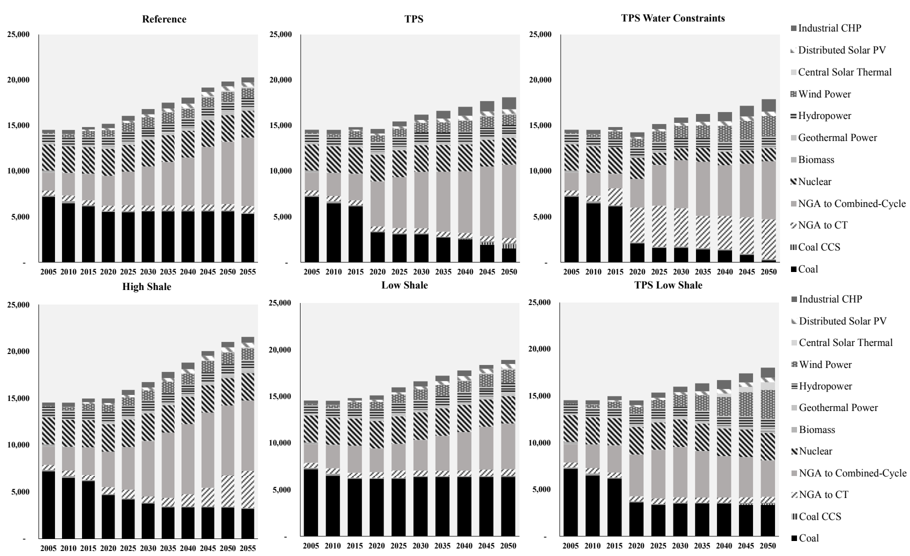

Figure 2. Electricity Generation Mix by Technologies and by Scenarios (in PJ)

In different scenarios, electricity generation technologies are various, though the share of generation from renewables are similar with the exclusion of TPS Low Shale (27% renewables by 2050) and TPS Water scenarios (21% renewables by 2050). Shale gas availability plays an important role in the future electricity generation mix in scenarios with or without CO_2 constraints in the electricity generation sector. The highest share of electricity generation from coal can be observed in the Low Shale scenario and the highest share of natural gas is in the High Shale scenario. In the TPS and TPS with water constraints scenarios most conventional coal plants that remained active through 2050 in the Reference and Low Shale scenarios, are gradually retired and replaced by natural gas power (combined cycle and combustion turbine plants). In the TPS scenario about 30% of the remaining coal facilities are retrofitted with CCS technology by 2045.

Rapid deployment of natural gas combustion turbines can be observed in the TPS scenario with water constraints in 2020 and later, though power plants with CCS do not deploy during the modeling period. Thus, in TPS scenarios, in place of the retired coal facilities, the model implements natural gas combined cycle or natural gas combustion turbines (depending on presence of water restraints as burning of natural gas in combustion turbines requires very little water and natural gas-fired combined cycle systems require water for cooling) or renewables (in case of shale gas limitation).

Furthermore, in the TPS scenario with water constraints, conventional nuclear plants are retired more rapidly and the model relies primarily on natural gas that replaces not only coal, but nuclear too. Solar and wind do not significantly contribute in electricity generation in the TPS Water Constraints scenario in comparison to the TPS Low Shale scenario.

ELECTRICITY GENERATION WATER CONSUMPTION AND WITHDRAWALS MODELING RESULTS

The water consumption figure reveals that shifts to less water-intensive technologies for electricity generation could be observed only in the TPS scenario with water constraints (Figure 3). In the Low Shale and Reference scenarios water consumption is correspondingly 20% and 25% higher by 2050 than in 2005. In the High Shale scenario water consumption is 8% higher and in TPS scenarios without water constraints water consumption in the electricity generation sector is about the same as in 2005 by 2050. Thus, CO_2 constraints encourage a decrease in water withdrawals in the generation sector in all TPS scenarios relative to the Reference scenario. At the same time, electricity generation water withdrawal in the Reference scenario drops 20% by 2020 relative to 2005 and stays about the same in 2020-2050. The reason is that existing coal power plants with once-through cooling systems are replaced by power plants with recirculating cooling systems that have a higher water consumption but lower water withdrawal. Water withdrawal in the Low Shale scenario is the highest across all scenarios (though 12% lower than in 2005) as less natural gas power plants can be deployed.

Coal plant retirement and the associated cooling system replacement play a major role in water withdrawal reductions in the scenarios with CO_2 constraints. Replacement of old facilities also increases generating efficiency and consequently decreases withdrawal. The shift to low water-use renewable power (wind or solar) can be observed only in TPS scenarios with water constraints and in the TPS scenario with Low Shale assumptions. The TPS Low Shale scenario does not show that withdrawal is lower than in TPS or High Shale scenarios as replacement of coal plants is limited by natural gas availability. In addition, CCS retrofits in the TPS Low Shale scenario are associated with higher levels of withdrawal.

By 2050, relative to the 2005, power generation sector water withdrawals decrease by 12%, 21% and 32%, respectively, in the Low Shale, High Shale and Reference scenarios. In the TPS scenario with water constraints, the trend toward more water-efficient technologies and cooling systems results in a 98% withdrawal reduction by 2040. Water withdrawal reductions in the TPS and TPS Low Shale scenario are 46% and 34%, respectively, by 2050. Thus, water withdrawal and consumption generally are lower in the scenarios with CO_2 constraints.

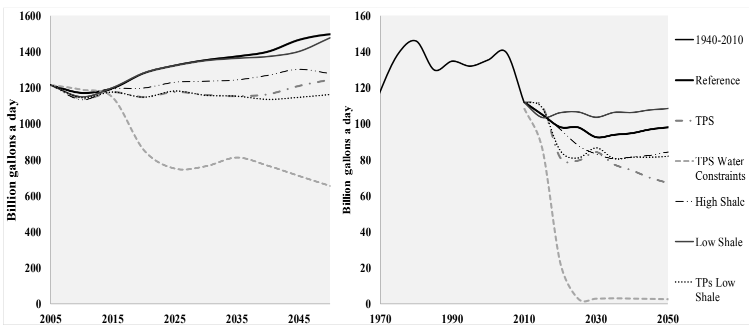

Figure 3. Water Consumption (left) and Water Withdrawals (right) in Electricity Generation Sector by Scenario.

The significance of electricity generation sector water demand depends to some extent on local conditions or on how much water is locally available and what water alternative uses would be. The greatest growth in water consumption in the electricity generation sector in the scenarios without water constraints is expected in West South Central, South Atlantic and Pacific regions or in the regions that are already experiencing intense competition over water. By 2050, in the scenarios without CO_2 constraints, water withdrawal drops in New England, East North Central, South Atlantic and Mountain regions in response to decreased electricity generation and replacement of once-through cooling systems by recirculating systems (Figure 4).

Thus, the response of power sector water consumption at the regional level is complex: in the scenarios with a CO_2 policy and without water constraint, national power sector water consumption is about the same as in 2005. At the regional level, water consumption could decrease, increase or stay the same in response to the replacement of inefficient existing conventional coal plants with higher efficiency natural gas combined cycle plants. These fluctuations occur at different times for each scenario, depending on the rate of conventional coal plant retirement and shale gas availability and each CO_2 emissions constraint scenario has an exclusive impact on total electric sector water usage at the regional level.

Regional water withdrawals remain at a generally static slope throughout the model horizon in New England, South Atlantic, West South Central and Pacific regions in the scenarios without water constraints. In the five other regions, if CO2 constraints take effect, water withdrawals are lower than in the reference scenario.

Future water demand in the electricity generation sector will be affected by the increase of electricity demand and by the power generation mix. The demand and generation mix projections vary, they are highly uncertain and depend on many factors, including market and economic conditions, energy policies, resource availability, technologies deployment and environmental regulations.

Though CO2 emissions reduction policies do not increase water withdrawals in the power sector in the TPS scenarios, water consumption over the model time horizon first slightly decreases, and then increases because CO2 constraints drove the replacement of existing thermoelectric power facilities cooled by once-through systems with more efficient facilities that decrease water withdrawal but increase consumption.

Footnotes

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