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Life cycle water use of coal- and natural-gas-fired power plants with and without carbon capture and storage

Yang Ou, Haibo Zhai*, Edward S. Rubin

College of Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

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ABSTRACT

This study conducts a hybrid life cycle analysis to estimate and characterize the water use of coal- and natural-gas-fired power plants with and without carbon capture and storage (CCS), including quantification of variability and uncertainty in the life cycle water use. The addition of CCS would remarkably increase the plant and life cycle water use, depending on the CO_2 capture level. The life cycle water use also varies with fuel type and cooling technology. Among multiple supply stages for electricity generation, the power plant operation dominates the life cycle water use for both types of power plants. The probabilistic simulation results show that the plant operation is the stage contributing the most to the uncertainty of life cycle water use for a pulverized coal-fired power plant, whereas the hydraulic fracturing is the dominant stage of uncertainty for a shale-gas-fired combined cycle power plant.

1. Introduction

Low-carbon energy production has been increasingly becoming important for mitigating climate change. To cut carbon dioxide (CO_2) emissions, the U.S. Environmental Protection Agency (EPA) has established CO_2 emission performance standards for new fossil fuel-fired power plants. The final standard for new coal-fired power plants is an emission limit of 1400 pounds of CO_2 per megawatt-hour on a gross-output basis (lb CO_2/MWh-gross), which is less stringent than the initially proposed standard of 1100 lb CO_2/MWh-gross (EPA, 2014, 2015a). For new natural gas combined-cycle (NGCC) plants, the standard is an emission limit of 1000 lb CO_2/MWh-gross (EPA, 2015a). The EPA also issued the Clean Power Plan under Section 111(d) of the Clean Air Act to reduce CO_2 emissions from existing power plants, which sets up state-specific emission targets to reduce nationwide carbon pollution by an average of 32% below 2005 levels in 2030 (EPA, 2015b). Carbon capture and storage (CCS) is regarded as one of the best emission reduction systems in the EPA's rules for new fossil fuel-fired electricity generating units (EGUs), whereas improved utilization of NGCC power plants is considered as one of the key mitigation measures for existing plants. However, retrofitting CCS for partial CO_2 capture also is a viable option for some existing coal-fired EGUs to comply with the Clean Power Plan, depending on unit attributes and fuel prices (Zhai et al., 2015). To comply with the CO_2 emission limit of 1100 lb/MWh gross, adding amine-based CCS to new pulverized coal-fired (PC) power plants would increase plant-level water use by roughly 20–50% (Talati et al., 2014). In addition, the high energy and infrastructure demands of CCS also contribute to natural resource use and chemicals used for CO_2 capture. When unconventional fuels such as shale gas are used to fire NGCC power plants, the production of shale gas requires large volumes of water for drilling and hydraulic fracturing, which could be several times of those for conventional natural gas production (Clark et al., 2013; Meldrum et al., 2013) and intensify pressure on local water resources (Soeder and Kappel, 2009). Depending on the availability of water resources at different supply chains for electricity generation, low-carbon energy regulations and policies could pose complex water management challenges for fossil fuel-fired power plants, and their impacts on water resources need to be examined on a life cycle basis.

Life cycle environmental impacts of CCS have received increasing attention (Koornneef et al., 2008; Korre et al., 2010; Singh et al., 2011; Zapp et al., 2012; Corsten et al., 2013; Grant et al., 2014; Zhang et al., 2014). However, less attention has been paid to the life cycle water use issue. Water withdrawal and water consumption are the two metrics that are often adopted to measure water use. Water withdrawal refers to the total amount of water taken from a source while consumption refers to the loss of water that is not returned to the source (e.g. due to evaporation) (Zhai et al., 2011). Meldrum et al. (2013) present consolidated estimates of life

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* Corresponding author.
E-mail address: hbzhai@cmu.edu (H. Zhai).

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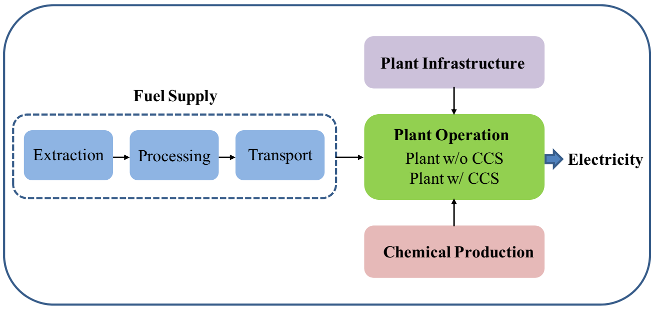

Fig. 1. Life cycle analysis boundary.

cycle water use for various electricity generation technologies by conducting a broad review and analysis on existing references and find that the plant operation for electricity generation dominates the life cycle water use for fossil fuel-fired power plants in most cases. When power generation is considered as end use of shale gas, hydraulic fracturing only accounts for 6.2% of the life cycle water consumption (Laurenzi and Jersey, 2013). In comparison, NGCC plants use much less water than PC plants (Meldrum et al., 2013; Fthenakis and Kim, 2010; Laurenzi and Jersey, 2013). Deterministic comparisons of water footprints among 36 coal-based power generation pathways show that life cycle water use is sensitive to the choice of fuel production and transport methods and the power plant configuration (Ali and Kumar, 2015). Adding CCS to PC and NGCC power plants would roughly double the life cycle water use (Fthenakis and Kim, 2010; Meldrum et al., 2013). However, existing life cycle studies on CCS mainly focus on 90% CO_2 capture and highly depend on water use data collected from various sources without sufficient access to power plant or system designs and quantification of variability and uncertainty. Besides, water used in plant infrastructure and chemicals production is not often included in the analysis.

The major objectives of this paper, therefore, are to (1) estimate and characterize the life cycle water use of coal- and natural-gas-fired power plants under the constraint of different CO_2 emission limits, especially the U.S. EPA's newly issued new source performance standards (NSPS) for limiting CO_2 emissions; (2) examine the variability in life cycle water use by key factors including fuel type and supply approach, and power plant and CCS designs (e.g. wet versus dry cooling; partial versus full CO_2 capture); and (3) quantify the uncertainties in major stages or supply chains across the life cycle to provide probabilistic water use estimates. When CO_2 capture is needed, commercially available amine-based CCS is employed for power plants. This study provides a systematic inventory and water implications of low-carbon electricity generation across the life cycle. The term of *water use* includes both water withdrawal and water consumption. Given that the U.S. EPA's rules present the standards in the English units, the variables of this study are expressed in the English unit system. However, unit conversion factors from English to metric unit systems are provided for international readers in the Appendix.

2. Material and methods

2.1. Overview of analysis scope and methods

In this analysis, the major stages of the life cycle for electric power generation include fuel acquisition, processing and transport, power plant operation, production of chemicals used in power plants, and power plant infrastructure. Fig. 1 shows the life cycle analysis scope, in which the fuel supply stage includes fuel extraction, processing and transport; the power plant operation stage covers water use for electricity generation; ammonia, limestone, and monoethanolamine (MEA) used in environmental control systems are included in the water analysis for chemical production; and the plant infrastructure stage mainly takes into account upstream component manufacturing and power plant construction. A process-based hybrid life cycle assessment (LCA) is conducted by incorporating relevant information from a power plant model with inventory databases and an Economic Input-Output -LCA tool for water use estimates. The life cycle water use measured in gallons per megawatt hour (gal/MWh) is estimated as:

$$LCWU = wuf^{FS} * \frac{FU}{E^{MW}} + wuf^{OP} + wuf^{CHE} * \frac{CHE}{E^{MW}} + wu^{PI} * \frac{1}{E^{MWh}} \qquad (1)$$

where $LCWU$ is the life cycle water use (gal/MWh); wuf^{FS} is the water use factor of fuel supply (gal/ton for coal, gal/MMscf for natural gas); wuf^{OP} is the water use factor of plant operation for electricity generation (gal/MWh); wuf^{CHE} is the water use factor of chemical production (gal/ton); wu^{PI} is the total water use for plant infrastructure (gal); CHE is the amount of chemical used in a power plant (ton/hr); FU is the amount of fuel used in a power plant (ton/hr for coal; MMscf/hr for natural gas); E^{MW} is the net plant power output (MW_{net}); E^{MWh} is the total electricity generation of power plant over the lifetime (MWh). The Integrated Environmental Control Model, a power plant modeling tool, serves as the basis for the process-based LCA and estimates a variety of mass and water streams at coal- and natural gas-fired power plants (IECM, 2012). The water use factors of fuel supply are estimated based on the existing data from literature. A life cycle inventory database is applied to estimate the water use factors of chemical production (Goedkoop et al., 2013), while an Economic Input-Output Life Cycle Assessment (EIO-LCA) tool is employed to estimate the water use factors of plant infrastructure (CMUGDI, 2015).

2.2. Water use by stage

2.2.1. Fuel supply

Coal can be extracted by surface mining or underground mining and transported mainly by trains or by slurry pipelines in occasional cases. Dust control inside the mine leads to more direct water use for underground mining than surface mining. Furthermore, extensive use of mine equipment for constructing the shaft and operation of ventilation fan also result in more indirect water use for underground mining (Fthenakis and Kim, 2010). Natural gas can be extracted by conventional drilling or hydraulic fracturing (mainly for shale gas) and transported mainly by pipelines (Meldrum et al., 2013). Water use may vary significantly with extraction site.

Meldrum et al. (2013) conducted a comprehensive review that collects and screens a wide range of references regarding water use for fuel production and electricity generation. To address the discrepancy among collected data because of the differences in production pathways, analysis boundaries, and performance parameters, their review study first conducts a harmonization analysis based on such key performance parameters as net plant efficiency and fuel heating value and then presents the minimum, median, mean and maximum estimates of fuel supply water use intensities in the form of gallons per MWh for both coal and natural gas (Meldrum et al., 2013). Thus, their water use intensity estimates are used in our analysis, including uncertainty analysis. Given that the water use factor required in Eq. (1) is on the basis of either mass or volume, the fuel supply water use factors in the form of gallons per ton (gal/ton) for coal or gallons per million standard cubic feet (gal/MMscf) for natural gas are derived or back-calculated from the reported water use intensities in terms of the common harmonization performance metrics.