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The cost of conserved water for coal power generation with carbon capture and storage in Alberta, Canada

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ABSTRACT

The impact of carbon capture and storage (CCS) technology on the coal-fired power generation was evaluated in this paper. The impact was measured through the cost of conserved water (CCW) as an indicator. This indicator was estimated by combining water demand coefficients and levelized cost of electricity (LCOE). CCW was calculated based on a reference case for each of the developed 66 generic pathways of coal-based power generation with CCS. The current existing mix of power generation in the Province of Alberta, Canada was taken as the reference case in this paper. Water consumption coefficients for coal-based power generation with CCS were found in the range 1.01–4.85 m^3/MWh based on the complete life cycle and 0.15–3.65 m^3/MWh for the power generation stage. Based on the complete life cycle boundary, pathways involved ultra-supercritical configuration and oxyfuel combustion CCS technology offer the lowest CCW, with values less than 0.89 USD per m^3 of water saved for consumption and less than 0.66 USD per m^3 of water saved for withdrawals. In the sensitivity analysis, LCOE for the pathways involved dry cooling was increased by 6.00 USD/MWh over the base case value, and the resulted corresponding increase in the CCW was found in the range 9–33% compared to the base case.

1. Introduction

Carbon capture and storage (CCS) is being proposed as a technology to mitigate greenhouse gas (GHG) emissions from coal-fired power plants as a process to capture CO_2 from exhaust gases of the burned fuel to be injected into a geological storage [1]. CO_2 geological storage has a drawback of increasing the underground pressure and may cause seismic actions and leakage of CO_2 can lead to severe environmental damage. CCS as new technology could have a major role to play in mitigation of GHG emissions from large-scale power generation based on fossil fuels or biomass or if utilized for biofuels production [2]. CCS is one of the most important determinant factors for the future of electricity generation from coal-fired power plants. National Energy Board (NEB) in Canada [3] linked between the reliability of CCS and its role to resolve high GHG emissions as the main obstacle facing the establishment of the new coal-fired power plants.

CCS is a technology with the intensive use of thermal energy and a range of 2.3–4.5 GJ per tonne of captured CO_2 can be consumed depending on the type of the technology used [4,5]. Solutions were proposed to alleviate this intensive energy use such as by integrating coal power plants with gas turbine and post-combustion CCS technology [6]. Coal-fired power plants have to be with improved efficiency to maintain the acceptable net power output after retrofitted with CCS. The efficient power plant can be achieved through new coal technologies include supercritical and ultra-supercritical boilers, integrated gasification combined cycle (IGCC), and fluidized bed combustion [7,8]. Genesee-3 [9] and Keephills-3 [10] are two new coal-fired power plants built in Alberta, Canada, with supercritical boilers to improve the efficiency and to reduce the GHG emissions. A large-scale CCS project was proposed with annual capacity about one million tonnes of CO_2 to be captured from the existing Keephills-3 power plant [11]. Domination of power generation in Alberta by coal power plants represents a stress on water resources due to the significant water required for cooling systems [12]. Agriculture irrigation represents a challenge for water supply in Alberta during spring and summer seasons, while petroleum and industrial activities need significant amounts of water during winter season [13].

Two of the main concerns accompanied the implementation of the current commercial CCS technologies on the coal-fired power plants are the increased water demand, and the increased cost of the power generated [14–17]. CCS is one of the essential solutions for global warming and can be carried out into three stages of processing CO_2 to cover capturing, transporting, and storing in a reservoir [18,19]. The negative impact on water and cost of power generation depends mainly on the technology used for the CCS and the techniques followed for CO_2 transport and storage. Post-combustion is suitable for retrofitting with the operating power plants [20], and it is recognized as one of the most developed technologies available in practical stage [21] compared to

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Nomenclature

CCS	carbon capture and storage
CCW	cost of conserved water
CON	conventional natural gas
CO_2	carbon dioxide
CP	cooling pond
CT	cooling tower
DC	dry cooling
DOE	U.S. Department of Energy
GHG	greenhouse gas
H_2	hydrogen
H_2O	water
IGCC	integrated gasification combined cycle
LCOE	levelized cost of electricity
$LCOE_A$	levelized cost of electricity in USD/MWh for the reference case
$LCOE_N$	levelized cost of electricity (in USD/MWh) generated from a coal-fired power plant with a CCS technology
Mt/year	metric tonne per year
m^3	cubic metre, a unit of volume in the metric system, equal to a volume of a cube with edges one metre
m^3/MWh	cubic metre of water per megawatt-hour of electricity generated
NEB	National Energy Board
NETL	National Energy Technology Laboratory
OTC	once-through cooling
OXF	oxyfuel combustion CCS technology
POC	post-combustion CCS technology
PRC	pre-combustion CCS technology
SM without REV	surface mining without revegetation
SM with REV	surface mining with revegetation
SUB	sub-critical pulverized coal
SUPER	supercritical pulverized coal
TWh	terawatt hour, equal one million MWh
ULTSUPER	ultra-supercritical pulverized coal
UM	underground mining of coal
USD	United States Dollar
WDC_A	water demand coefficient in m^3/MWh for the reference case
WDC_N	water demand coefficient (in m^3/MWh) for a coal-fired power plant with a CCS technology
WGS	water-gas-shift

the other CCS pathways such as oxyfuel and pre-combustion. In spite of the great challenges facing the CCS technology, still, new plants are being developed all over the world [22,23]. According to the Global CCS Institute [24], although of the additional costs and risks associated with CCS projects in power generation, construction of a post-combustion capture project in Canada (Boundary Dam) and an integrated gasification combined cycle (IGCC) project in Kemper County was continuing.

The current situation of power generation mix in Alberta is one of the motivations for this paper. Power generation in Alberta is dominated by coal-fired power plants [25], and consequently, the concern is focused on the GHG emissions from this sector. The share of electricity generation in the total GHG emissions of Alberta was 35% during 2011 [26]. The Climate Change Strategy planned by the Government of Alberta was to reduce GHG emissions by 200 Mt/year by 2050 compared to the business-as-usual case and 70% of this reduction expected to be achieved through CCS technology. Initially, Alberta had announced in July 2008 a fund of $2-billion to implement this plan [27]. Coal-fired power plants operating in Alberta would be shut down by 2030 and moving towards more cleaner technologies was proposed to mitigate the intensive GHG emissions from power generation [28].

Most of the earlier studies to evaluate the environmental and economic impacts of CCS technologies on coal power generation were conducted independently [29–32], and interdisciplinary studies are scarce [33]. The cost of conserved water (CCW) methodology was used to integrate economic and water demand indicators to evaluate comparatively the sustainability of renewable energy pathways [34]. Sanders et al. [35] related the environmental and economic impacts by highlighting the effect of applying water use fees on the power generation in Texas. Some plans to mitigate GHG emissions from power generation have overlooked the impacts on other natural resources such as water and land [27,28,36,37]. This paper is to fill some gaps left from earlier studies. The key objectives of this paper are to:

- Develop water demand coefficients for 66 pathways of coal-power generation retrofitted with CCS technology.
- Introduce the CCW as an indicator for evaluation of CCS technologies.
- Evaluate the impacts of CCS technologies on the sustainability of coal-based power generation in Alberta.
- Combine two different factors for evaluation through integrating water demand and the cost of power generation.
- Identify the most sustainable and cost-effective CCS technology to be retrofitted with the coal power plant.

2. Methods

Generic water demand coefficients represented by consumption and withdrawals besides the levelized cost of electricity (LCOE) were developed for the coal-based power generation with the consideration for the incremental increase would be resulted from the retrofitting of the CCS technology. An earlier study conducted by Ali and Kumar [38] derived water consumption and withdrawal coefficients for systems without CCS and harmonized in this paper according to the conversion efficiency. The current weighted average for water demand coefficients (consumption and withdrawals coefficients) and LCOE for the power generation in Alberta, Canada, estimated and taken as a reference to calculate the cost of conserved water (CCW). The LCOE considered for the pathways involved dry cooling in the base case is increased by 6.00 USD/MWh in the sensitivity analysis to study the impact of increased electricity generation cost on the CCW.

2.1. Metric for comparison

CCW is introduced in this paper as an indicator to integrate LCOE and water-demand coefficients. CCW is then used to conduct a comparative assessment of the coal power generation pathways retrofitted with CCS technology. The same concept of CCW followed in this study was used by the National Energy Technology Laboratory (NETL) [39] to assess dry cooling compared to the wet recirculating cooling system. Ku and Shapiro [40] have also used CCW and taken pulverized coal power plant using cooling towers as a reference to assess the new alternatives for power generation technologies. CCW is given by [34,39,40]:

$$CCW = \frac{LCOE_N - LCOE_A}{WDC_A - WDC_N} \quad (1)$$

where