Energy 86 (2015) 335–343

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Life-cycle comparison of greenhouse gas emissions and water consumption for coal and shale gas fired power generation in China

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A R T I C L E I N F O

Article history:
Received 27 August 2014
Received in revised form
7 April 2015
Accepted 8 April 2015
Available online 16 May 2015

Keywords:
Coal
Shale gas
Electric power generation
Life cycle assessment

A B S T R A C T

China has the world's largest shale gas reserves, which might enable it to pursue a new pathway for electricity generation. This study employed hybrid LCI (life cycle inventory) models to quantify the ETW (extraction-to-wire) GHG (greenhouse gas) emissions and water consumption per kWh of coal- and shale gas-fired electricity in China. Results suggest that a coal-to-shale gas shift and upgrading coal-fired power generation technologies could provide pathways to less GHG and water intensive power in China. Compared to different coal-fired generation technologies, the ETW GHG emissions intensity of gas-fired CC (combined cycle) technology is 530 g CO_2e/kWh, which is 38–45% less than China's present coal-fired electricity. Gas-fired CT (combustion turbine) technology has the lowest ETW water consumption intensity at 960 g/kWh, which is 34–60% lower than China's present coal-fired electricity. The GHG-water tradeoff of the two gas-fired power generation technologies suggests that gas-fired power generation technologies should be selected based on regional-specific water resource availabilities and electricity demand fluctuations in China. However, the low price of coal-fired electricity, high cost of shale gas production, insufficient pipeline infrastructures, and multiple consumers of shale gas resources may serve as barriers to a coal-to-shale gas shift in China's power sector in the near term.

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1. Introduction

Electric power systems account for around half of global primary energy use, and this primary energy use is expected to grow rapidly with rising demand for electricity-based services such as lighting, cooking, sanitation, heating and cooling, and information and communications [1,2]. Coal plays a vital role in electricity generation worldwide, with a 48% share of global electricity generation in 2011. Coal's share of global electricity generation has been fairly stable for nearly the past four decades—varying between 38% and 40%—while the fraction of natural gas used for electricity has grown steadily from 12% in 1973 to 23% in 2012 [3]. Given its widespread abundance, its affordability, and its technological maturity, coal-fired electricity is likely to play a dominant role in global energy supplies for the foreseeable future [4]. As such, coal is likely to remain a predominant source of global GHG (greenhouse gas) emissions moving forward as well.

China's booming economy has driven rapid growth in the nation's electricity production and consumption, and has recently made China the largest power producer and consumer in the world, with a 22% share of global electricity generation in 2012 [5]. China's electric power sector heavily relies on coal consumption, which accounted for 75% of the nation's total electricity generation in 2010 [6]. As a result, coal-fired power generation currently comprises 42% of China's total combustion-related GHG emissions [7,8] and is a major contributor to hazardous air pollutants and air quality problems in many of the nation's urban regions.

Compared to coal, natural gas is a relatively clean fuel for power generation given that it releases only about one-third to one-half of the CO_2 (carbon dioxide) and almost no particulate matter or SO_2 (sulfur dioxide) for the same amount of electricity production [2]. Evidence of the GHG emissions reduction benefits of a shift from coal to natural gas for electric power can be seen in the United States, where, over the period 2008–2012, the share of coal in U.S.

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http://dx.doi.org/10.1016/j.energy.2015.04.034
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electricity output fell from 49% to 37%, while natural gas increased from 21% to 30% [9]. The transition from coal to natural gas led to an associated drop in the CO_2 emissions intensity of U.S. electric power generation—from 603 g/kWh to 533 g/kWh—over the same period [10,11]. The United States' recent coal-to-gas shift was enabled primarily by a rapid increase in shale gas development, which increased U.S. natural gas production by 21% from 2006 to 2011 [12].

China is at the beginning of a similar shale gas development boom. As of 2013, China was estimated to have the world largest shale gas reserves at approximately 31 trillion cubic meters (m^3) [13]. The Chinese government has set ambitious targets for developing its vast shale gas resources, and aims to reach production levels of 60–100 billion m^3 per year by 2020 [14]. These targets may be hard to reach, however, due to high drilling costs, unfavorable geology, and yet-unidentified sweet spots [15,16]. For example, it was projected that China's annual production might only reach 20 billion m^3 per year by 2020, and 60 billion m^3 per year by 2030 [17]. Recent estimates of the net energy yield of Chinese shale gas well development suggest that under different production scenarios, net energy yields over the period 2013–2020 could reach 1650–7150 PJ, which equates to approximately 45–200 billion m^3 natural gas [18]. Thus, in the near term, ample resources of shale gas in China might be employed as a cleaner burning alternative to coal for use in electricity generation. Such a coal-to-gas shift may play a key role in a transition toward a lower-carbon electricity generation mix in China over next few decades.

Despite the advantages of vast shale gas reserves and relatively cleaner combustion of natural gas, switching from coal to shale gas for power generation in China is controversial because of growing social and environmental concerns associated with hydraulic fracturing, which include land occupation, induced seismicity, air pollution, and water consumption and contamination [19]. Furthermore, the cumulative GHG emissions of shale gas extraction, distribution, and combustion still contribute to climate change. As such, shale gas is a transitional strategy for China's long-term carbon mitigation, with increasing deployment of low-carbon energy sources such as nuclear, hydro, and renewable power being vital to long-term emissions reductions. Given that electricity and natural gas prices in China are primarily set by the central government, a coal-to-gas shift in the nation's power sector would be primarily driven by government regulations and policies, and would be affected by economic factors such as gas price, the capital cost of natural gas power plants, and a carbon price [20]. Sound policy design in China requires a LCA (life-cycle assessment) approach for understanding the implications of shifting fuels for power generation, and which considers the entire ETW (extraction to wire) system and its associated inputs and outputs of resources and pollutants [2].

Existing LCA studies have compared the life cycle energy use and GHG emissions of using coal, conventional natural gas, and shale gas for power generation, but these studies have been mostly focused on case studies in the United States [21–25]. By comparison, the literature on China's use of shale gas is scarce due to the country's nascent shale gas industry. Furthermore, existing calculations of the energy and environmental footprints of coal-fired and natural gas-fired power generation in China mainly employ process-based LCI (life cycle inventory) models and are limited to life-cycle energy consumption and GHG emissions [26,27]. One limitation of process-based LCI models is that they inherently truncate analysis system boundaries [28], which causes truncation errors and different ETW process systems across studies [29]. These truncation errors and study boundary incompatibilities preclude credible comparisons of power generation system LCIs for China. Furthermore, water consumption is a critical environmental issue associated with power generation, but life cycle water consumption data are scarce in previous Chinese studies. Lastly, given that multiple technology options exist for coal- and gas-fired electricity generation, ETW footprint studies and comparisons should consider all plausible generation technologies available to China.

This article addresses these knowledge gaps in two important ways, both of which represent novel contributions to the literature. First, a comprehensive ETW inventory is presented using a hybrid approach that includes both process-based data for specificity to China and IO-based methods to ensure a broad system boundary. Second, the ETW GHG emissions and water consumption footprints of coal- and shale gas-fired electricity in China are compared on a per-kWh generated basis. The results presented here can help policy makers and researchers better understand the resource and GHG footprints of both coal- and shale gas-fired electricity in China, which can inform cleaner power transition pathways.

2. Methodology

The ETW GHG emissions and water consumption of power generation in China were estimated using a hybrid LCI modeling approach with system boundaries inclusive of fuel extraction and processing, fuel transportation, and power generation. This study employed IO (input–output) and input-output-based (IO-based) hybrid LCI modeling approaches for coal and shale gas extraction, respectively. Process LCI models using specific Chinese data were employed for analyzing fuel transportation and power generation systems in China including multiple power generation technologies. Fig. 1 provides an overview of the methodology, included power generation technologies, and the ETW system boundaries used in this study.

The IO LCI model used for analyzing coal mining and washing was based on a previously developed China IO LCI model [30]. The IO-based hybrid approach used for analyzing shale gas extraction and processing was based on published data that combined IO sector modeling with specific process LCI data for shale gas production in China [31]. The functional unit of this study is 1 kWh of generated electricity at the wire leaving the power plant. ETW GHG emissions and water consumption were considered, the latter of which is defined as the water permanently withdrawn from its source. Water consumption is distinct from water withdrawals, which includes both water consumption and water that is extracted but later returned to its source.

The IO LCI model employed in this study was developed using 2007 China economy benchmark data [32]. Sectoral energy and GHG emission data were obtained from the China Statistical Yearbook [33] and the world input–output database [34]. The China Statistical Yearbook on Environment includes data on water withdrawals of agriculture, industry, households, and eco-environment [35], and the China Water Resource Bulletin contains data on water consumption for these sectors [36]. These aggregated statistics were allocated to detailed sectors in the China IO-LCI model based on the fraction of each sector's purchase from the water supply sector in the 2007 China Input-Output Table [32]. See the Supplementary Information (SI) for full model development details.

For coal-fired power generation in China, this study considered prevailing technology types (i.e., subcritical, supercritical, and ultra supercritical pulverized coal power generation) and IGCC (integrated gasification combined cycle) systems [37,38], which is a promising technology for more efficient power generation. For gas-fired power generation, this study considered CT (combustion turbines) and CC (combined cycle) systems, the two prevailing technologies for natural gas power plants. For all technologies, this study adopted the latest publicly available data to reflect current

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