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Development of life cycle water footprints for gas-fired power generation technologies

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A R T I C L E I N F O

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A B S T R A C T

The key objective of this paper is to develop a benchmark for water demand coefficients of the complete life cycle of natural gas-fired power generation. Water demand coefficients include water consumption and water withdrawals for various stages of natural gas production as well as for power generation from it. Pathways were structured based on the unit operations of the types of natural gas sources, power generation technologies, and cooling systems. Eighteen generic pathways were developed to comparatively study the impacts of different unit operations on water demand. The lowest life cycle water consumption coefficient of 0.12 L/kW h is for the pathway of conventional gas with combined cycle technology, and dry cooling. The highest life cycle consumption coefficient of 2.57 L/kW h is for a pathway of shale gas utilization through steam cycle technology and cooling tower systems. The water consumption coefficient for the complete life cycle of cogeneration technology is in the range 0.07–0.39 L/kW h and for withdrawals ranged 0.10–14.73 L/kW h.

1. Introduction

It is expected that natural gas production and demand will increase due to the diversity of its applications, well-established technologies of extraction and conversion, cost competiveness, and attractiveness to environmentalists as a cleaner fuel than other fossil fuels such as coal and oil on combustion. The water footprints for power generation from natural gas can be evaluated through the life cycle assessment (LCA) which is considered as a useful tool in the research community to conduct comparative analysis of the environmental impacts [1]. The province of Alberta is one of the largest natural gas producers in North America and dominates about 70% of the total production in Canada. Other unconventional gas resources in Alberta are coal-bed methane (CBM) which is representing 8% of the total production and about 0.1% from shale gas [2]. Shale gas is one of the unconventional sources that have started to contribute significantly to the production of natural gas. The annual natural gas production in Canada is expected to reach 0.21 trillion cubic meters (tcm) by 2025, and 40% of this production will be from unconventional gas [3]. Researchers, policy makers, and the public have raised concerns about the extraction of this unconventional gas and its environmental impact on water [4–6]. Water use for electricity generation has been a key issue as some power plants have been forced to shut down or have reduced generation due to the water shortage [7,8].

The generation of power through natural gas is expected to increase because of its availability and its ability to compete with other fossil fuels and renewable sources of energy. It has been expected that by 2035 natural gas will overcome coal as the most used source for electricity generation in the world [9]. Natural gas is also used for cooking, space heating, transportation, hydrogen production, and petrochemical industries, where it is converted to heat or used as a feedstock.

The unit operations associated with natural gas are those related to primary fuel extraction and processing. The impact on the water demand varies according to the natural gas source and the technologies used for processing and transportation. The type of technology and cooling system used for power generation from natural gas are essential unit operations in determining the amount of water required. Electricity can be generated from natural gas without the use of steam through single cycle while combined cycle (NGCC), the steam cycle, and cogeneration necessitate the use of water for steam make-up and cooling [10–12].

Most studies carried out in the water–energy nexus consider only the power generation stage [13–15] without taking into account the fuel cycle, some recognize only water consumption without considering intensive water withdrawals for power generation stage [16–18], and comprehensive studies, including fuel life cycle water demand through detailed pathways, are scarce. Other

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Nomenclature

CBM	coal-bed methane
CHP	combined heat and power
COE	water consumption/withdrawals coefficient in liters of water per m^3 of natural gas for upstream pathways
DOE	department of energy
EIA	the U.S. Energy Information Administration
HHV	higher heating value
kJ	kiloJoule, unit of energy equal to 1000 J
LCA	life cycle assessment
L/kW h	liters of water per kW h of electricity generated
L/year	liters of water per year of operation
m^3	cubic meter, a unit of volume in the metric system, equal to a volume of a cube with edges one meter
NGCC	natural gas combined cycle
tcm	trillion cubic meters, equal to 10^{12} m
U.S.	United States of America
WDC	water consumption/withdrawals coefficient in liters of water per kW h generated in upstream pathways
η	conversion efficiency of the power plant from fuel heat content up to the electricity generated
η_{cc}	total conversion efficiency of a NGCC power plant
η_{cg}	conversion efficiency of a cogeneration gas-fired power plant
η_{pst}	the conversion efficiency of the portion of power generated by steam cycle in an NGCC power plant
η_{sc}	conversion efficiency of a single cycle gas-fired power plant
η_{st}	conversion efficiency of a steam cycle gas-fired power plant

than that, the broad effects of boundaries, technologies, and power plant's performance on the variability of water demand coefficients have not been captured through sensitivity analysis in earlier studies [19]. There has been study on life cycle water demand on power generation from coal [20]. Grubert et al. [21] addressed natural gas and coal power generation through complete life cycle for specific geographical boundary (Texas) and for specific technology (NGCC).

One of the motivations to estimate water demand for the first stage of primary fuel extraction is due to the fact that the geographical location of natural gas resources is not controlled by humans, unlike the locations of power plants, which of necessity have to be located near a water source.

The aim of this paper is to develop a life cycle water demand benchmark for power generation from natural gas. The key objectives of this study are:

- To develop and estimate the life cycle water demand for gas-fired power generation including plants with advanced conversion technologies.
- To provide a comparative assessment of the water demand of eighteen different pathways in the conversion of natural gas to power. Pathways were structured to cover the full life cycle based on the unit operations of the gas source, power generation technology, and cooling system used.
- To assess the impacts on the complete life cycle water demand coefficients from using minimum, maximum, and average coefficients of the different unit operations.

2. Methodology

Water demand coefficients were developed to include water consumption and water withdrawals. Water consumption term is defined by USGS [22] to include part of the water withdrawals that is not returned back to the source. This part can be consumed through evaporation (for example from the cooling system of a thermal power plant), transpiration, or direct consumption by a product. Water withdrawal is defined as the total amount of water that diverted from a source.

Water demand coefficients are defined as the amount of water consumed and water withdrawn per unit power generation over life cycle and related as follows:

$$\text{Water with drawals} = \text{Water consumption} + \text{Returned water} \quad (1)$$

Natural gas is consumed either in power generation pathways or for heat and other applications. Effects on water demand due to conversion to heat and applications of natural gas other than power generation are not covered in this study, except in the case of cogeneration technology which is covered in a separate section 4.4. Each pathway of electricity generation from natural gas consists of a number of unit operations. This includes unit operations for production of natural gas, its processing, transportation and utilization of power production. Upstream pathways are divided according to the type of natural gas source. Power generation pathways are branched according to the unit operations that affect the water footprints significantly.

In this study, data were developed, gathered from the literature and harmonized at the assumed conversion efficiency for each technology. In the base case, average values for the data are used to represent water demand coefficients for the various upstream and downstream unit operations involved in power generation from natural gas. These developed water demand coefficients for each unit operations are used to estimate the complete life cycle water demand coefficient of gas-fired power generation. Only fresh water was considered in this study. A comprehensive sensitivity analysis is carried out in order to study the uncertainty of using average values in the base case on the complete life cycle water demand coefficients. The average data are taken as the most likely in Monte Carlo simulations model with the consideration for the minimum and maximum values. Annual water consumption and water withdrawals were calculated for each pathway for a 1000 MW gas-fired power plant with assumed capacity factor 80% (7000 h/year). The unit operations and system boundary considered for this study are shown in Fig. 1.

2.1. Selection of gas-fired power generation pathways

Gas-fired power generation pathways are branched according to the technology and cooling system used. Technologies used to generate power from natural gas are single cycle, steam cycle, and NGCC. In this study four types of cooling systems are investigated including once-through cooling, cooling tower, cooling pond, and dry cooling [20].

2.1.1. Single cycle

Gas-fired power plants with single cycle work on the principle of the Brayton cycle by burning a mixture of pressurized air and fuel in a chamber. The exhaust gases are expanded into the turbine, which spins to generate electricity and drive the compressor [10]. When the gas turbine reaches a high temperature, it needs to be cooled to improve the conversion efficiency. Wet compression, the injection of water into the compressor inlet, is one of the