Applied Energy 147 (2015) 556–568

Contents lists available at ScienceDirect

Applied Energy

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

Life cycle assessment of hydrogen production from underground coal gasification

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HIGHLIGHTS

- Life cycle assessment (LCA) conducted for H_2 production from UCG with CCS.
- Process modeling approach applied for LCA.
- H_2 production from UCG–CCS more environmentally benign than SMR–CCS.
- Sensitivity of key UCG parameters on GHG emissions considered.

ARTICLE INFO

Article history:
Received 24 October 2014
Received in revised form 3 February 2015
Accepted 1 March 2015
Available online 24 March 2015

Keywords:
Underground coal gasification (UCG)
Life cycle assessment (LCA)
Hydrogen production
Carbon capture and sequestration (CCS)
GHG emissions

ABSTRACT

Western Canada is endowed with considerable reserves of deep un-mineable coal, which can be converted to syngas by means of a gasification process called underground coal gasification (UCG). The syngas can be transformed into hydrogen (H_2) through commercially available technologies employed in conventional fossil-fuel based H_2 production pathways. This paper presents a data-intensive model to evaluate life cycle GHG emissions in H_2 production from UCG with and without CCS. Enhanced oil recovery (EOR) was considered as a sequestration method and included in the LCA. The life cycle GHG emissions are calculated to be 0.91 and 18.00 kg-CO_2-eq/kg-H_2 in H_2 production from UCG with and without CCS, respectively. In addition, a detailed analysis of the influence of key UCG parameters, i.e., H_2O-to-O_2 injection ratio, ground water influx, and steam-to-carbon ratio in syngas conversion, is completed on the results. The advantage of adopting UCG–CCS technology for H_2 production is realized over the predominant steam methane reforming (SMR) process; around 15.3 million tonnes of GHG emissions can be mitigated to achieve the projected SCO production rate from the bitumen upgrading in 2022. Furthermore, the sensitivity analysis showed that the life cycle GHG emissions is sensitive to the heat exchanger efficiency and the separation efficiency of the pressure swing adsorption (PSA) unit, with increasing values of these parameters causing an increase and a decrease in the magnitude of life cycle GHG emissions, respectively.

1. Introduction

Crude oil production from the Canadian oil sands contributed around 51 Mega tonnes (Mt) to Alberta's total greenhouse gas (GHG) emissions of 244 Mt in 2010 [1]. Synthetic crude oil (SCO) production from the Canadian oil sands is anticipated to rise to 1.26 million bpd in 2022 [2], and hydrogen (H_2) demand to upgrade bitumen to SCO, will rise in a corresponding manner. Around 21 kg-H_2 is required to upgrade one cubic meter of bitumen to SCO, which translates to a hydrogen demand of 4.2 Mt/day to produce 1.26 million bpd of SCO in 2022 [3,4]. Currently, H_2 is produced from the steam methane reforming (SMR) process, using natural gas (NG) as a feedstock [5,6]. Since SMR-based H_2 production has high GHG footprint – 9.1–14.49 kg-CO_2-eq/kg-H_2 [3,7–11] – there is reason to study alternative ways to produce H_2 for sustainable development of the bitumen upgrading industry.

Underground coal gasification (UCG) involves injecting gasifying agents in an underground coal seam to produce syngas, which can be used to produce electricity, hydrogen, liquid fuels, etc. [12,13]. UCG not only reduces fugitive emissions, ash residues, etc., but reduces costs of coal mining, coal handling, coal transport, and coal gasifiers [12,14–16]. Furthermore, CO_2 sequestration can be combined with UCG, mainly because of the close proximity of CO_2 sequestration sites with the un-mineable coal reserves [17–19]. Therefore, keeping in mind the abundant coal reserves in Alberta,

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http://dx.doi.org/10.1016/j.apenergy.2015.03.009
0306-2619/

Nomenclature

ASU	air separation unit
ACTL	Alberta Carbon Trunk Line
CCS	carbon capture and sequestration
CO_2-eq	carbon dioxide equivalent
EOR	enhanced oil recovery
FUNNEL-EGY-H2-UCG	**FUN**damental e**N**gineering principl**E**s-based mode**L** for estimation of **E**ner**GY** consumption and production in hydrogen (**H2**) production from **U**nderground **C**oal **G**asification
FUNNEL-GHG-H2-UCG	**FUN**damental e**N**gineering principl**E**s-based mode**L** for estimation of **G**reen**H**ouse **G**ases in hydrogen (**H2**) production from **U**nderground **C**oal **G**asification
GEMIS	Global Emissions Model for Integrated Systems
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions and Energy Use in Transportation
GT	gas turbine
GWP	global warming potential
HP	high pressure
HRSG	heat recovery steam generator
Kg	kilogram
LCA	life cycle assessment
LCI	life cycle inventory
LHV	lower heating value
LP	low pressure
MJ	megajoule
Mt	million tonne
MW	megawatt
MWh	megawatt hour
NER	net energy ratio
NG	natural gas
NGSR	natural gas steam reforming
PSA	pressure swing adsorption
SCG	surface coal gasification
SCO	synthetic crude oil
SMR	steam methane reforming
SRR	syngas reforming reactor
ST	steam turbine
WGSR	water gas shift reactor
d	depth of well, meter
E	diesel energy consumption in well drilling, megajoule

which are estimated to be in the range of 2–3 trillion tons,[1] UCG along with carbon capture and sequestration (CCS) can potentially be an environmentally benign H_2 production pathway [20–23]. More recently, the feasibility and the operation of UCG for syngas production in Alberta was successfully demonstrated by Swan Hills Synfuels LP [24].

A life cycle assessment (LCA) is a potent tool that uses a cradle-to-grave approach to evaluate the environmental impact of a system [8]. An LCA deals mostly with product systems and focuses on environmental assessment and corresponding consequences. An LCA allows for characterization of the consequences of possible public policy options or scientific alterations and development of novel sustainable energy resources and technologies [8,10,25,26]. There are a large number of studies in the literature that evaluate environmental competitiveness of various H_2 production pathways (both renewable and non-renewable) by implementing LCA. Lee et al. [27] conducted an LCA of H_2 production from naphtha steam reforming, natural gas steam reforming (NGSR), liquefied petroleum gas steam reforming, and water electrolysis with wind power. They concluded that the H_2 production from water electrolysis with wind power has the least global warming potential (GWP). Ozbilen et al. [28] concluded that H_2 production from thermochemical water decomposition cycles is less GHG intensive as compared to NGSR. In another study by Ruether et al. [29], an LCA for H_2 fuel production in the United States from liquefied natural gas (LNG) and coal was applied. The results of the analysis showed that although H_2 production from coal gasification is more GHG intensive than from LNG gasification, implementation of CCS has a larger environmentally favorable effect with coal than with LNG [29].

Pereira and Coelho [30] integrated the Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) model and the Global Emissions Model for Integrated Systems (GEMIS) to conduct a well-to-wheel analysis of H_2 production from wind and solar energy for Portugal. Moreover, Dufour et al. [31] implemented the LCA of various NG-based H_2 production pathways (i.e., SMR, SMR–CCS, thermal and autocatalytic decomposition of NG) by using SimaPro software. They concluded that H_2 production from SMR–CCS led to 67% lower GHG emissions than conventional SMR. Aspen Plus software was used to conduct a simulation of large-scale H_2 production from water splitting thermo-chemical cycle and the obtained results were then used to implement the LCA in [32]. Furthermore, an exergetic LCA of H_2 production from wind and solar energy showed that although the use of wind and energy has lower fossil and mineral consumption, the cost of H_2 production is 2.25–5.25 times higher than SMR-based H_2 production [9]. Cetinkaya et al. [7] reported that for large-scale operation of H_2 production, NGSR, coal gasification, and thermochemical water splitting with copper–chlorine cycles are more beneficial than wind and solar energy-based pathways.

However, while extensive work has been carried out regarding the LCA of conventional and unconventional H_2 pathways, the evaluation of UCG from an LCA perspective and its comparison with other H_2 production pathways in the literature is very limited. With this in mind, the LCA conducted in this paper will provide a reliable and comprehensive estimate of the GHG mitigation potential of UCG-based H_2 production. The estimates developed in this research can contribute to the sustainable development of GHG intensive sectors, where a considerable hydrogen demand exists (e.g. Western Canada's bitumen upgrading industry). In addition, the insight gained from the LCA has the potential to help the governmental in development and formulation of appropriate policy, and industry in making investment decisions on large-scale implementation of UCG, especially in a carbon constrained energy economy such as Alberta's. Furthermore, the LCA will facilitate the identification of vital areas for minimizing the GHG footprint of a fossil fuel based energy system like UCG.

In this paper, two scenarios – H_2 from UCG with CCS[2] and without CCS – were considered to quantify the environmental competitiveness over conventional methods such as SMR, SMR–CCS, SCG and SCG–CCS. An LCA model – FUNNEL-GHG-H2-UCG (**FUN**damental e**N**gineering principl**E**s-based mode**L** for estimation of **G**reen**H**ouse **G**ases in hydrogen (**H2**) production from **U**nderground **C**oal **G**asification) – is developed to estimate the GHG emissions in H_2

[1] It is reported that around 16% of Alberta's total coal reserves, located in the upper Mannville coal zone in Alberta, can be recovered through UCG [20].

[2] This scenario follows the Government of Alberta's target of reducing GHG emissions by 139 Mt through CCS projects in 2050 [1].