

Life cycle assessment of hydrogen production from underground coal gasification



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HIGHLIGHTS

- Life cycle assessment (LCA) conducted for H₂ production from UCG with CCS.
- Process modeling approach applied for LCA.
- H₂ production from UCG–CCS more environmentally benign than SMR–CCS.
- Sensitivity of key UCG parameters on GHG emissions considered.

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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 (H₂) through commercially available technologies employed in conventional fossil-fuel based H₂ production pathways. This paper presents a data-intensive model to evaluate life cycle GHG emissions in H₂ 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-CO₂-eq/kg-H₂ in H₂ production from UCG with and without CCS, respectively. In addition, a detailed analysis of the influence of key UCG parameters, i.e., H₂O-to-O₂ 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 H₂ 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.

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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 (H₂) demand to upgrade bitumen to SCO, will rise in a corresponding manner. Around 21 kg-H₂ 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, H₂ is

produced from the steam methane reforming (SMR) process, using natural gas (NG) as a feedstock [5,6]. Since SMR-based H₂ production has high GHG footprint – 9.1–14.49 kg-CO₂-eq/kg-H₂ [3,7–11] – there is reason to study alternative ways to produce H₂ 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, CO₂ sequestration can be combined with UCG, mainly because of the close proximity of CO₂ sequestration sites with the un-mineable coal reserves [17–19]. Therefore, keeping in mind the abundant coal reserves in Alberta,

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Nomenclature

ASU	air separation unit	Kg	kilogram
ACTL	Alberta Carbon Trunk Line	LCA	life cycle assessment
CCS	carbon capture and sequestration	LCI	life cycle inventory
CO ₂ -eq	carbon dioxide equivalent	LHV	lower heating value
EOR	enhanced oil recovery	LP	low pressure
FUNNEL-EGY-H ₂ -UCG	FUNDamental eNGineering principleS-based model for estimation of ENERGY consumption and production in hydrogen (H ₂) production from Underground Coal Gasification	MJ	megajoule
FUNNEL-GHG-H ₂ -UCG	FUNDamental eNGineering principleS-based model for estimation of GreenHouse Gases in hydrogen (H ₂) production from Underground Coal Gasification	Mt	million tonne
GEMIS	Global Emissions Model for Integrated Systems	MW	megawatt
GHG	greenhouse gas	MWh	megawatt hour
REET	Greenhouse Gases, Regulated Emissions and Energy Use in Transportation	NER	net energy ratio
GT	gas turbine	NG	natural gas
GWP	global warming potential	NGSR	natural gas steam reforming
HP	high pressure	PSA	pressure swing adsorption
HRSG	heat recovery steam generator	SCG	surface coal gasification
		SCO	synthetic crude oil
		SMR	steam methane reforming
		SRR	syngas reforming reactor
		ST	steam turbine
		WGSR	water gas shift reactor
		<i>d</i>	depth of well, meter
		<i>E</i>	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 H₂ 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 H₂ production pathways (both renewable and non-renewable) by implementing LCA. Lee et al. [27] conducted an LCA of H₂ 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 H₂ production from water electrolysis with wind power has the least global warming potential (GWP). Ozbilen et al. [28] concluded that H₂ 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 H₂ fuel production in the United States from liquefied natural gas (LNG) and coal was applied. The results of the analysis showed that although H₂ 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 (REET) model and the Global Emissions Model for Integrated Systems (GEMIS) to conduct a well-to-wheel analysis of H₂ production from wind and solar energy for Portugal. Moreover, Dufour et al. [31] implemented the LCA of various NG-based H₂ production pathways (i.e., SMR, SMR-CCS, thermal and autocatalytic decomposition of

NG) by using SimaPro software. They concluded that H₂ 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 H₂ 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 H₂ production from wind and solar energy showed that although the use of wind and energy has lower fossil and mineral consumption, the cost of H₂ production is 2.25–5.25 times higher than SMR-based H₂ production [9]. Cetinkaya et al. [7] reported that for large-scale operation of H₂ 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 H₂ pathways, the evaluation of UCG from an LCA perspective and its comparison with other H₂ 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 H₂ 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 – H₂ from UCG with CCS² 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 (FUNDamental eNGineering principleS-based model for estimation of GreenHouse Gases in hydrogen (H₂) production from Underground Coal Gasification) – is developed to estimate the GHG emissions in H₂

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].

production from UCG with and without CCS. In addition, FUNNEL-GHG-H₂-UCG takes into account the life cycle GHG emissions associated with CO₂ transportation and sequestration, which none of the aforementioned studies [3,8,31] have considered. Following [33], a process modeling approach is applied to estimate the operation emissions in the two scenarios. In this paper, the GHG emissions are estimated based on pertinent data inputs to represent western Canadian conditions as closely as possible.

The paper is structured in the following manner: Section 2 outlines the methodology adopted for the LCA. The results and discussion, and comparative analysis are provided in Sections 3 and 4, respectively. Finally, the conclusions are presented in Section 5.

2. Methodology

An LCA is a technique used to evaluate the energy and material use associated with an energy production pathway or a product [34]. Moreover, the results of the LCA can help to identify key processes that can be improved to reduce the overall environmental impact [10]. Overall, the LCA methodology can be implemented to evaluate the life cycle GHG emissions associated with an energy production pathway. As per ISO 14040 and ISO 14044 [35], there are four steps for conducting an LCA – goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation. The first step aims to distinctly define the goal and scope of the study. The purposes for carrying out the LCA and the intended audience are described in the goal of the study. The description of the functional unit used in the current analysis, the unit operations to be studied, and the system boundary are emphasized in the scope of the LCA. The second step – life cycle inventory analysis – involves estimation, calculation or measurement of the energy and material flows within the systems boundary. The third step – life cycle impact assessment – refers to the identification of the impact categories e.g., GWP, human impact, land use, etc., and to allocating the data collected to the appropriate impact categories. Lastly, in the life cycle interpretation step, the results from steps 2 and 3 are combined to evaluate the environmental impact as per the goal of the study. Additionally, appropriate conclusions and recommendations are prepared.

2.1. Goal and scope

The purpose of this analysis is to evaluate life cycle GHG emissions from H₂ production from UCG. This paper evaluates two scenarios, H₂ production from UCG with CCS (scenario 1) and H₂ production from UCG without CCS (scenario 2) in Alberta. A geological sequestration method – enhanced oil recovery (EOR) – is used for carbon storage in scenario 1.³

2.1.1. Functional unit

The functional unit chosen in this paper is 1 kg of H₂. This analysis reports GHG emissions and energy use associated with different unit operations involved in the H₂ production pathway. GHG emissions are reported as kg-CO₂-eq/kg-H₂. The net energy ratio (NER), which is a measure of “useful energy” (i.e., H₂ and electricity) production by the system per unit energy consumption of the fossil fuel (i.e., coal), is defined in Eq. (1).

$$\text{NER} = \frac{\text{H}_2 \text{ energy output (MW)} + \text{Electricity export (MW)}}{\text{Fossil energy input (MW)}} \quad (1)$$

³ EOR was purposefully selected to put into perspective the Government of Alberta's decision to fund a large-scale CCS project, the Alberta Carbon Trunk Line (ACTL) [5]. The ACTL will include a 16 in., 240 km CO₂ pipeline, which will transport CO₂ from Fort Saskatchewan, Alberta to an EOR site in Clive, Alberta [5].

2.1.2. System boundaries

Fig. 1 depicts system boundaries for scenario 1 and scenario 2. The starting point of both scenarios is the injection of gasifying agents (H₂O and O₂) through an injection well in an underground coal reactor, which upon gasification produces syngas. The syngas is collected by a production well and is converted to H₂ using conventional technologies employed in SMR- and SCG-based H₂ production pathways. It is important to mention that both scenarios are characterized with capture of CO₂ using a physical solvent – Selexol.⁴ Pure H₂ reaches a bitumen upgrading facility by a pipeline after its separation in a PSA unit, and compression. Downstream of the PSA unit, the remaining un-separated gas, called purge gas, is combusted in a combined cycle plant to produce electricity and steam. A portion of the purge gas is burned separately to satisfy the heat duty of a syngas reforming reactor (SRR) in the syngas-to-H₂ conversion section. In scenarios 1 and 2, GHG emissions are mainly associated with combustion of the purge gas in the gas turbine (GT) and the burner in the syngas-to-H₂ conversion section. However, scenario 2 has additional GHG emissions from CO₂ venting of the CO₂ captured by the Selexol system. The underlying difference between the two scenarios is the absence of CO₂ compression, transportation, and sequestration in scenario 2. In scenario 1, the captured CO₂ is compressed till it reaches a supercritical state and then transported through a pipeline to the sequestration site.

Electricity requirement in different unit operations (see Fig. 1) is offset by electricity production in an on-site co-generation plant, and a syngas expander placed after UCG. Additional electricity produced is exported to the grid outside the system boundary, and appropriate emissions credit is awarded. Moreover, diesel use in well drilling, and H₂ and CO₂ pipeline construction (see Fig. 1) is placed inside the system boundary; emissions associated with diesel production and distribution are also considered. Similarly, steel use in pipeline construction is placed inside the system boundary. The system boundary termination point is the bitumen upgrading facility for both scenarios. It is worth mentioning that the emissions associated with CO₂ capture, compression, and transportation are allocated to H₂ production.

2.2. Life cycle inventory (LCI)

This step includes identification of all unit operations within the system boundary and the quantification of corresponding inputs and outputs [34]. Of the several methodologies for data collection e.g. direct measurement, literature review and process modeling [34], the life cycle inventory (LCI) is conducted by incorporating the results of the FUNNEL-EGY-H₂-UCG (FUNdamental eNginEering principleS-based modeL for estimation of ENERgy consumption and production in hydrogen (H₂) production from Underground Coal Gasification) developed and presented in [33]. However, in some unit operations of the presented work, the data is collected from the literature and developed as required.

2.2.1. H₂ production from UCG

The plant size for H₂ production is based on gasification of a deep highly volatile B bituminous Manville coal seam. The total gasified coal amount is 118 tonnes per day. The H₂ output is estimated to be 16.28 tonnes per day for a H₂O-to-O₂ injection ratio of 2, and a ground water influx of 0.4 m³/tonne of coal [33]. Tables 1 and 2 show the composition of coal chosen in the study and the key assumptions associated with different unit operations of the H₂ production pathway from UCG for both scenarios. The H₂

⁴ A higher calorific value of purge gas – 55.15 kJ/kg – is achieved in scenario 2 upon CO₂ removal against a calorific value of 3.15 MJ/kg when no CO₂ removal takes place in scenario 2 [33,36]. In addition, the purge gas compression power requirement ahead of the GT is also reduced [33].

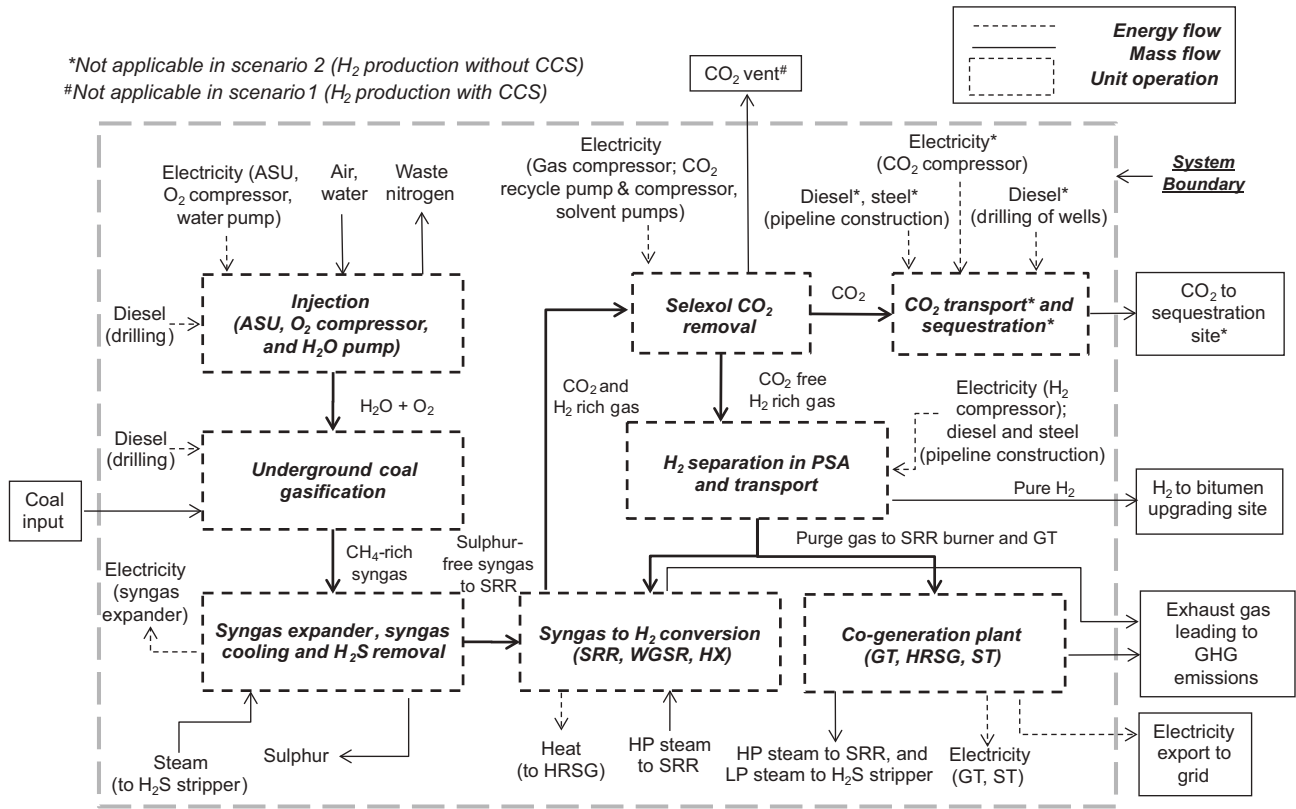


Fig. 1. System boundary of the study. The boundaries are the same for scenarios 1 and 2, except for the absence of CO₂ transport, and sequestration in the latter scenario. Notes: ASU-air separation unit; SRR-syngas reforming reactor; WGSR-water gas shift reactor; HX-heat exchanger; GT-gas turbine; HRSG-heat recovery steam generator; ST-steam turbine.

Table 1
Coal composition assumed in the study. Data adapted from [6,24].

Ultimate analysis		Proximate analysis	
Parameter	%	Parameter	%
Ash	9.7	Moisture	4.7
Carbon	74.5	Ash	9.3
Hydrogen	3.6	Volatile Matter	30.5
Nitrogen	1.1	Fixed Carbon	55.5
Sulphur	0.4		
Oxygen	10.7		
LHV of coal, MJ/kg		28.5	

production plant lifetime is assumed to be 40 years and is applicable for both scenarios [6]. The details on the process modeling of the unit operations are given in [33]. It is worth noting that owing to the complexity of the unit operations in the PSA, H₂ separation was modeled as a simple separation process⁵ by assuming a separation efficiency of 85% [33,36,37]. Furthermore, the heat exchanger network for steam generation was modeled in a similar fashion⁶ as employed by authors in [33,37].

Table 3 shows the key energy inputs and outputs associated with various unit operations in scenarios 1 and 2. In scenario 1, nearly 91.6% CO₂ is captured [33]; the total flow of captured CO₂ is evaluated to be 247.8 tonne/day [33]. It is important to mention

⁵ Post CO₂ capture, the constituents of the H₂-rich and CO₂-free gas (input gas stream to PSA unit) (see Fig. 1) were split into two gas streams – H₂-rich gas, containing 85% of the H₂ in the input gas stream, and purge gas, containing the remaining constituents of the input gas stream [37].

⁶ The heat recovered from different unit operations was aggregated and then used for steam production in the co-generation section. A heat exchanger efficiency of 60% was assumed for the base case conditions.

that, of the total gas captured, around 97.4% is CO₂, 0.8% is CH₄, while the remaining gases are non-GHGs.

2.2.2. Drilling

UCG involves drilling for the formation of an injection well and a production well. A horizontal drilling technique is used to connect both wells. Injection and production well depth are both assumed to be 1400 m, whereas the length of the horizontal section is 1400 m [24]. Diesel is used for drilling the wells. Total energy consumption in well drilling is calculated based on a correlation developed by Brandt [42] for drilling operations in Canada. Brandt [42] discussed two correlations for diesel use to represent low intensity (Eq. (2)), and high intensity (Eq. (3)) drilling operations; *d* is the depth of well, meters; *E* is the diesel energy consumed in drilling a well of depth *d*, in MJ. An average of the results obtained from the two correlations was used to account for diesel use in drilling in this paper.

$$E = 128.765 \cdot d^* \exp(0.469 \cdot d/1000) \tag{2}$$

$$E = 366.707 \cdot d^* \exp(0.399 \cdot d/1000) \tag{3}$$

2.2.3. CO₂ pipeline specification and EOR well characteristics for sequestration

It is important to reiterate that the operating and infrastructure emissions associated with CO₂ capture, compression, transport, and sequestration are allocated to H₂ production. This is mainly because the primary objective of CO₂ sequestration through EOR is to store the un-wanted CO₂ and not to produce more oil from depleted oil reservoirs.⁷

⁷ See note 2.

Table 2

Key assumptions for calculation of power requirement and production in the different unit operations in scenarios 1 and 2.

Parameter	Applicable scenario	Values	Sources/comments
<i>UCG, syngas to H₂ conversion</i>			
H ₂ O to O ₂ injection ratio in UCG	1,2	2	[24,33]
Ground water influx, m ³ /tonne of coal	1,2	0.4	[33,38]
Steam-to-carbon ratio in SRR ^a	1,2	3	[33,37]
<i>CO₂ compressor^b</i>			
Compressor isentropic efficiency	1	0.75	[39]
<i>GT</i>			
Mechanical efficiency	1, 2	99.5%	[40]
Isentropic efficiency	1,2	88%	[36]
Turbine inlet temperature, °C	1,2	1300	[36]
Pressure ratio	1,2	14.8	[36]
<i>HRSG, ST</i>			
HP steam temperature, °C	1,2	510	Based on steam energy requirement in the SRR [33,37]
HP steam pressure, bar	1,2	30	
LP steam temperature, °C	1,2	302	Based on steam energy requirement in the H ₂ S stripper [33,36]
LP steam pressure, bar	1,2	6	
Isentropic efficiency	1,2	85%	[41]
Mechanical efficiency	1,2	99.5%	[40]
Pump efficiency	1,2	75%	[36]
Heat exchanger efficiency	1,2	60%	[33]

^a Calculated based on the molar flow of CO and CH₄ in the syngas, which is fed to SRR.

^b Applicable for compression of CO₂ which is captured using Selexol technology, in a five-stage compressor train.

Pipeline is assumed to be the mode of transportation of CO₂ to the geological sequestration site. This is applicable for scenario 1 only. CO₂ is transported as a fluid in its supercritical state; a

Table 3

Input data and assumptions for different unit operations in H₂ production from UCG with and without CCS.

Parameter	Values		Source
	Scenario 1	Scenario 2	
Coal input, tonne/day	118	118	[24,33]
H ₂ output, tonne/day	16.28	16.28	[33]
Injection (ASU, O ₂ compressor, H ₂ O pump) ^a , MW	1.07	1.07	[33]
Syngas expander power output, MW	1.58	1.58	[33]
H ₂ S removal (Claus and tail gas treatment plant) ^b , MW	0.02	0.02	[33]
SelexolCO ₂ removal, MW	1.14	1.14	[33]
CO ₂ compressor ^c , MW	0.96	0	[33]
H ₂ compressor, MW	0.02	0.02	[33]
Gas turbine power output, MW	1.16	1.16	[33]
Steam turbine power output, MW	1.46	1.46	[33]
Total power consumption, MW	3.21	2.25	
Total power output, MW	4.20	4.20	[33]
Net electricity export to grid ^d , MW	0.93	1.83	[33]

^a Based on an O₂ input of 45 tonne/day; O₂ and H₂O injection pressure is 20 MPa and 14 MPa, respectively.

^b H₂S captured with using Selexol. Sulphur is recovered in a Claus plant after stripping of H₂S from the solvent.

^c The captured CO₂ is compressed above its critical pressure to around 15 MPa using a five-stage compressor train for suitable pipeline transportation.

^d Difference of total power output and total power consumption. A loss of 6.5% is assumed while transmission of electricity from the H₂ production plant to the grid.

distance of 100 km from the H₂ production plant to an EOR site is taken as the base case. Based on a pipeline operating pressure of 10.3 MPa [43], the pipeline diameter is calculated by a model developed by Ogden [44]. An iterative methodology is adopted to match an assumed diameter value with the calculated value obtained from the model [44]. CO₂ pipeline is manufactured from carbon steel, with a wall thickness of 15 mm [45–47]. Pipeline construction is also associated with use of a trencher. A trencher model Vermeer T555, suitable for CO₂ pipeline construction is chosen and a trench depth of 3 feet is assumed [48]. Diesel fuel consumption for the given trencher model is 0.88 m³/day [48]. GHG emissions associated with pipeline construction are amortized over a lifetime of 30 years [46].

Table 4

EOR well reservoir characteristics for CO₂ sequestration.

Parameter	Value	Sources/comments
Depth of reservoir ^a , m	1635.4	[49]
Reservoir thickness ^a , m	27.2	[49]
Reservoir pressure ^a , MPa	14.7	[49]
Permeability of reservoir, md	5	[39]
CO ₂ leakage rate per annum	0.01%	Applicable over 100 years [50,51]
Life of EOR well, years	25	Average life of an oil well ranges from 20 to 30 years [52]

^a Average of range of values for different EOR pilot projects in Alberta.

Table 5

LCI data associated with H₂ production from UCG with and without CCS.

Parameter	Values	
	Scenario 1	Scenario 2
<i>Injection</i>		
Amortized diesel use in drilling of UCG injection and production wells, MJ-diesel/kg-H ₂	0.016	0.016
<i>H₂ production</i>		
Heat requirement in SRR unit, MJ/kg-H ₂	17.41	17.41
Total heat recovered by HRSG, MJ/kg-H ₂	53.04	53.04
Total electricity consumed in H ₂ production, MJ/kg-H ₂	17.03	11.93
Total electricity produced in H ₂ production, MJ/kg-H ₂	22.30	22.30
Total electricity export in H ₂ production, MJ/kg-H ₂	4.93	9.69
HP steam use in SRR unit, MJ/kg-H ₂	52.71	52.71
HP steam produced in co-generation plant, MJ/kg-H ₂	52.71	52.71
LP steam produced in co-generation plant, kJ/kg-H ₂	232.20	232.20
LP steam use in sulphur recovery unit, kJ/kg-H ₂	232.20	232.20
Total CO ₂ captured in H ₂ production, tonne-CO ₂ /day	247.8	247.8
Total GHGs vented (after CO ₂ removal), tonne-CO ₂ -eq/day	0.0	293.0
CO ₂ produced from exhaust of GT and purge gas burner, tonne-CO ₂ -eq/day	24.8	24.8
<i>H₂ pipeline transport</i>		
Amortized diesel use in H ₂ pipeline construction, MJ-diesel/kg-H ₂	0.033	0.033
Total steel use in H ₂ pipeline construction, tonne	6093.2	6093.2
Amortized steel use in H ₂ pipeline construction, kg-steel/kg-H ₂	0.047	0.047
<i>CO₂ transport and sequestration</i>		
Amortized diesel use in CO ₂ pipeline construction, MJ-diesel/kg-H ₂	0.030	–
Total steel use in CO ₂ pipeline construction, tonne	1578.7	–
Amortized steel use in CO ₂ pipeline construction, kg-steel/kg-H ₂	0.009	–
Amortized diesel use in drilling of CO ₂ sequestration well, MJ-diesel/kg-H ₂	0.010	–

After reaching the EOR site, CO₂ is then injected in an EOR well reservoir (only applicable for scenario 1). Table 4 shows EOR well reservoir characteristics considered in the present analysis. Given that reservoir characteristics are site-specific [49], it is worth mentioning that an average of a range of values is used. With the assumed reservoir characteristics and the CO₂ flow rate, the total number of wells required is calculated by using a method developed by McCollum and Ogden [39]. The GHG emissions associated with drilling EOR wells were calculated using the methodology discussed in Section 2.2.2.

2.2.4. H₂ pipeline specification

Highly pure (99.99%) H₂ is delivered at a pressure of 0.2 MPa after its separation in PSA [33,36]. Pipeline is assumed to be the mode of transportation of H₂ to a bitumen upgrading site. A pipeline length of 100 km is considered as the base case for H₂ pipeline transportation. Typical hydrogen pipeline operating pressure and diameter range from 0.1 to 0.3 MPa and 0.25 to 0.30 m, respectively [53]. Considering small-scale H₂ production from UCG and its transportation, a lower value of diameter – 0.25 m is used for pipeline diameter. The compressor power requirement is calculated using Panhandle equation adopted in a similar model developed by Ogden [44]; compressor efficiency is assumed to be 55% [44]. Pipeline construction material and wall thickness are assumed to be carbon steel and 0.75 mm, respectively [54]. Diesel consumption for trenching up to a depth of 1.22 m is calculated using the same assumptions discussed in Section 2.2.3 [54]. The GHG emissions associated with H₂ pipeline construction were amortized over a lifetime of 22 years [53].

Based on the discussion above, Table 5 summarizes the LCI data associated with different unit operations of H₂ production with and without CCS. Appropriate emissions factors are allocated to the material and energy use (listed in Table 5) to evaluate the life cycle GHG emissions in scenarios 1 and 2.

2.3. Global warming potential (GWP) and main sources of GHG emissions

The environmental impact of a product or energy production pathway over its life cycle can be studied using different environmental indicators. In the present study, GWP – represented by kg-CO₂-eq/kg-H₂ – is the only impact category of interest. The GWP of other greenhouse gases than CO₂ i.e., CH₄ and nitrous oxide have been accounted for and converted to the CO₂-eq. This paper utilizes a 100-year time horizon for the GWP that is consistent with reporting under the Intergovernmental Panel on Climate Change (IPCC) 2007 report [55].

Operation emissions are associated with combustion of the purge gas (applicable for scenarios 1 and 2) and CO₂ venting from the CO₂ removal section (applicable for scenario 2). The steam

Table 6
Emission factors associated with fuel and material use and the GWPs of GHGs relative to CO₂.

Parameter	Value	Source
<i>Emission factors</i>		
Grid-electricity use ^a , tonnes-CO ₂ -eq/MWh	0.88	[56]
On-site electricity production ^b , tonnes-CO ₂ -eq/MWh	-0.65 ^b	[56]
Diesel use, kg-CO ₂ -eq/MJ	0.074	[3]
Production of virgin steel, kg-CO ₂ -eq/kg-steel	4.972	[3]
<i>GWP</i>		
CO ₂	1	[3]
CH ₄	25	[3]
N ₂ O	298	[3]

^a Applicable for Alberta, Canada.

^b Negative value indicates a credit will be given for electricity supply from the site to the grid.

requirement in the various unit operations is fulfilled by an in-house co-generation facility. It is important to mention that average emission factors of 0.048 and 0.040 kg-CO₂-eq/kg-H₂ were used to account for construction and manufacturing of the H₂ production plant in scenarios 1 and 2, respectively [29]. The GHG emissions associated with infrastructure are aggregated to evaluate non-operation GHG emissions. The gross life cycle GHG emissions are the sum of operation and non-operation GHG emissions (see Eq. (4); the units are in kg-CO₂-eq/kg-H₂). A credit is given for the export of electricity (in the case of a net positive electricity production) to the grid. Net life cycle GHG emissions are then calculated using Eq. (5). Again the units used in Eq. (5) are kg-CO₂-eq/kg-H₂. Table 6 summarizes emission factor values associated with fuel and material use (listed in Table 5) and the GWP of various GHGs.

Gross life cycle GHG emissions

$$= \text{Operation emissions} + \text{Non-operation GHG emissions} \quad (4)$$

Net lifecycle GHG emissions

$$= (\text{Gross lifecycle GHG emissions}) \\ - (\text{Emissions credit for supply of electricity to grid}) \quad (5)$$

2.4. Parametric analysis

This paper discusses the effect of key UCG process parameters (H₂O-to-O₂ injection ratio, ground water influx and steam-to-carbon ratio) on life cycle GHG emissions, both quantitatively and qualitatively. The steam-to-carbon ratio is an important process parameter for syngas-to-H₂ conversion in a conventional SCG-based H₂ production plant [36]. Chiesa et al. [36] examined the effect of steam-to-carbon ratio at the inlet of a high temperature WGS in H₂ production from SCG; reducing the value of the steam-to-carbon ratio from 1.48 to 0.55 increases the emissions by 45%. The steam-to-carbon ratio is fixed based on the quality of the syngas produced after UCG and the desired percentage of carbon conversion into CO₂ in the WGSRs and SRR. Furthermore, the syngas composition varies with in-situ coal composition and depth. Therefore, the degree of freedom to vary the steam-to-carbon ratio is project specific and is appropriately chosen based on the plant design specification i.e., H₂ production, electricity production in the co-generation plant and GHG emissions.

The H₂O-to-O₂ ratio plays a significant role in the composition of syngas and stability of the UCG operation [24,57]. The process control of the UCG operation is challenging and involves dynamic control of the H₂O-to-O₂ ratio to achieve a stable quantity and quality of syngas [24]. The degree of freedom to vary the H₂O-to-O₂ ratio was 2 to 3, consistent with the range used in a recent UCG pilot scale project in Alberta [24]; 3 being the maximum value of the ratio [24]. Therefore, it is important to understand the effect of this ratio on H₂ production output and life cycle GHG emissions. Moreover, this allows for choosing an injection strategy to facilitate higher syngas quality [57]. Ground water influx in the UCG affects the quality and the quantity of the produced syngas, which ultimately affects the H₂ output [12,13]. Since the ground water influx is difficult to estimate, a range of values – 0–0.4 m³/tonne-coal is considered for analysis [12,13,33].

3. Results and discussion

3.1. Life cycle GHG emissions

Table 7 shows a detailed breakdown of operation and non-operation emissions in scenario 1 and 2 estimated by

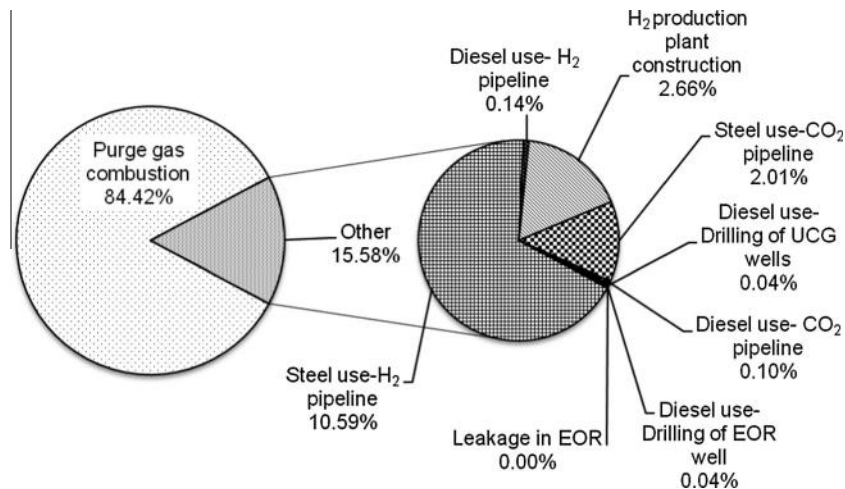


Fig. 2. Life cycle GHG emissions distribution in scenario 1 (H₂ production from UCG with CCS). “Other” indicates non-operation GHG emissions. The distribution is based on gross life cycle GHG emissions.

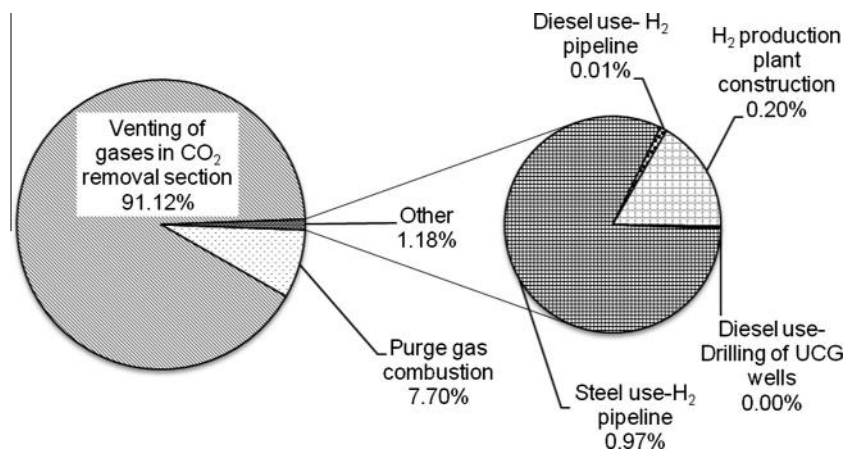


Fig. 3. Life cycle GHG emissions distribution in scenario 2 (H₂ production from UCG without CCS). “Other” indicates non-operation GHG emissions. The distribution is based on gross life cycle GHG emissions.

FUNNEL-GHG-H₂-UCG. Since the H₂ production pathway in both scenarios is self-sufficient in terms of electricity consumption (see Table 3), there are no GHG emissions for electricity use. The operation emissions in scenario 1 comprise purge gas combustion emissions, whereas in scenario 2, in addition to purge gas combustion emissions, there are emissions associated with venting of gases in the CO₂ removal section. The advantage of the co-generation is realized in both scenarios; the H₂ production pathway is self-sufficient in terms of steam and heat production.⁸ This ultimately negates the GHG emissions associated with steam and heat use in different process units – SRR, WGSRs and H₂S stripper.

In scenario 1, approximately 91.6% of CO₂ is captured; around 204 kWh of electricity is required to capture and compress one tonne of CO₂. Non-operation emissions are mainly associated with steel and diesel use in H₂ and CO₂ pipeline construction and with diesel use in drilling. Gross life cycle GHG emissions are estimated

to be 1.8 and 19.8 kg-CO₂-eq/kg-H₂ in scenarios 1 and 2, respectively. Contrastingly, net life cycle GHG emissions, which are calculated using Eq. (5), are lower than the gross life cycle GHG emissions because of a credit for net positive electricity production in scenarios 1 and 2. It is worth mentioning that the credit awarded in scenario 1 is less than in scenario 2 because of higher net electricity production in scenario 2 than in scenario 1 (see Table 3). The net life cycle emissions are evaluated to be 0.9 and 18.0 kg-CO₂-eq/kg-H₂ in scenarios 1 and 2, respectively.

Figs. 2 and 3 show a detailed distribution of operation and non-operation GHG emissions in scenarios 1 and 2, respectively. The operation emissions in scenario 1 are mainly associated with combustion of the purge gas, which contribute around 84.4% to gross life cycle GHG emissions. On the other hand, non-operation emissions are around 15.6% of gross GHG emissions. Of the total non-operation emissions, 68.8% are associated with H₂ pipeline construction, while the remaining 31.2% are attributed to CO₂ pipeline construction, drilling of wells in the UCG plant and the EOR site, EOR well leakage, and H₂ production plant construction. Since the diameter of the H₂ pipeline is greater than the diameter of the CO₂ pipeline, the GHG emissions associated with steel use is greater in the former case than the latter case.

Apart from emissions associated with purge gas combustion in scenario 2 (which contribute only 7.4% to gross life cycle GHG

⁸ FUNNEL-GHG-H₂-UCG is developed in such a way that the heat and steam demand always matches with the heat and steam supply. The model calculates the steam requirement in the SRR, WGSRs and H₂S stripper, and appropriate amount of steam is bled from the co-generation section. An increase in steam demand leads to a decrease in electricity output by the ST or vice versa. Similarly, the model calculates the heat requirement in the SRR unit and allocates appropriate amount of purge gas (main source of heat) to the burner of the SRR and the co-generation plant. An increase in heat requirement also leads to lower GT power output or vice versa.

emissions), the operation emissions also include emissions from venting of gases in the CO₂ removal section (contributing around 91.1% to gross life cycle GHG emissions). Non-operation emissions contribute only 1.18%. Of the total non-operation emissions in scenario 2, 83% are associated with H₂ pipeline construction, while the remaining 17% are from drilling the UCG wells and H₂ plant construction. Clearly, there are no GHG emissions associated with drilling, leakage in the EOR well, and CO₂ pipeline construction in scenario 2. Overall, the significance of non-operation emissions

with respect to gross life cycle GHG emissions can be appreciated in scenario 1 more than in scenario 2. This is because adoption of CCS technology in the former scenario results in lower operation emissions than in the latter scenario. It is worth noting that emissions associated with coal surface mining, coal mine development, and coal transport are negated in H₂ production from UCG, unlike in H₂ production from surface coal gasification (SCG) [7,14]. The notion of similarity of processes of syngas to H₂ conversion in UCG and SCG is complimented by the fact that the contribution of the operation emissions in the gross life cycle emissions (around 97.8%) in UCG is almost equivalent to reported values of 97% in SCG [7]. A higher percentage in UCG may be attributed to zero emissions associated with coal transport and coal mining.

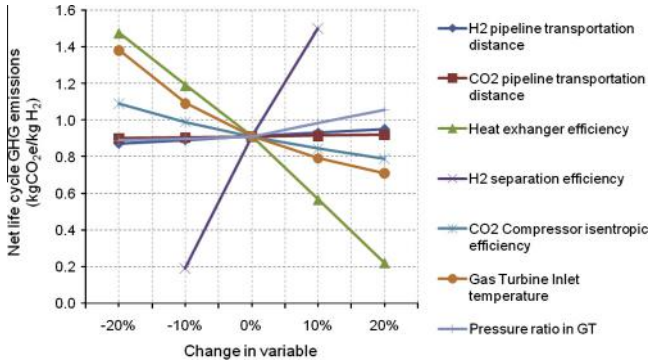


Fig. 4. Sensitivity analysis for scenario 1. The analysis is done for base case assumptions (the H₂O-to-O₂ injection ratio is 2, ground water influx is 0.4 m³/tonne of coal, and the steam-to-carbon ratio is 3).

3.2. Sensitivity analysis

A sensitivity analysis was conducted to understand the influence of various input parameters on net life cycle GHG emissions. A variation of ±20% in the input parameters was done to appreciate their effects on the results. Fig. 4 shows the sensitivity analysis completed for scenario 1 using base case assumptions. CO₂ and H₂ pipeline transportation distance are found to have weak sensitivities towards net life cycle GHG emissions owing to their low contribution towards the total values. Nevertheless, the net life cycle GHG emissions increase slightly with an increase in transportation distance owing to an increase in diesel and steel use in pipeline construction. The isentropic efficiency of the CO₂ compressor and the pressure ratio in GT are found to have a

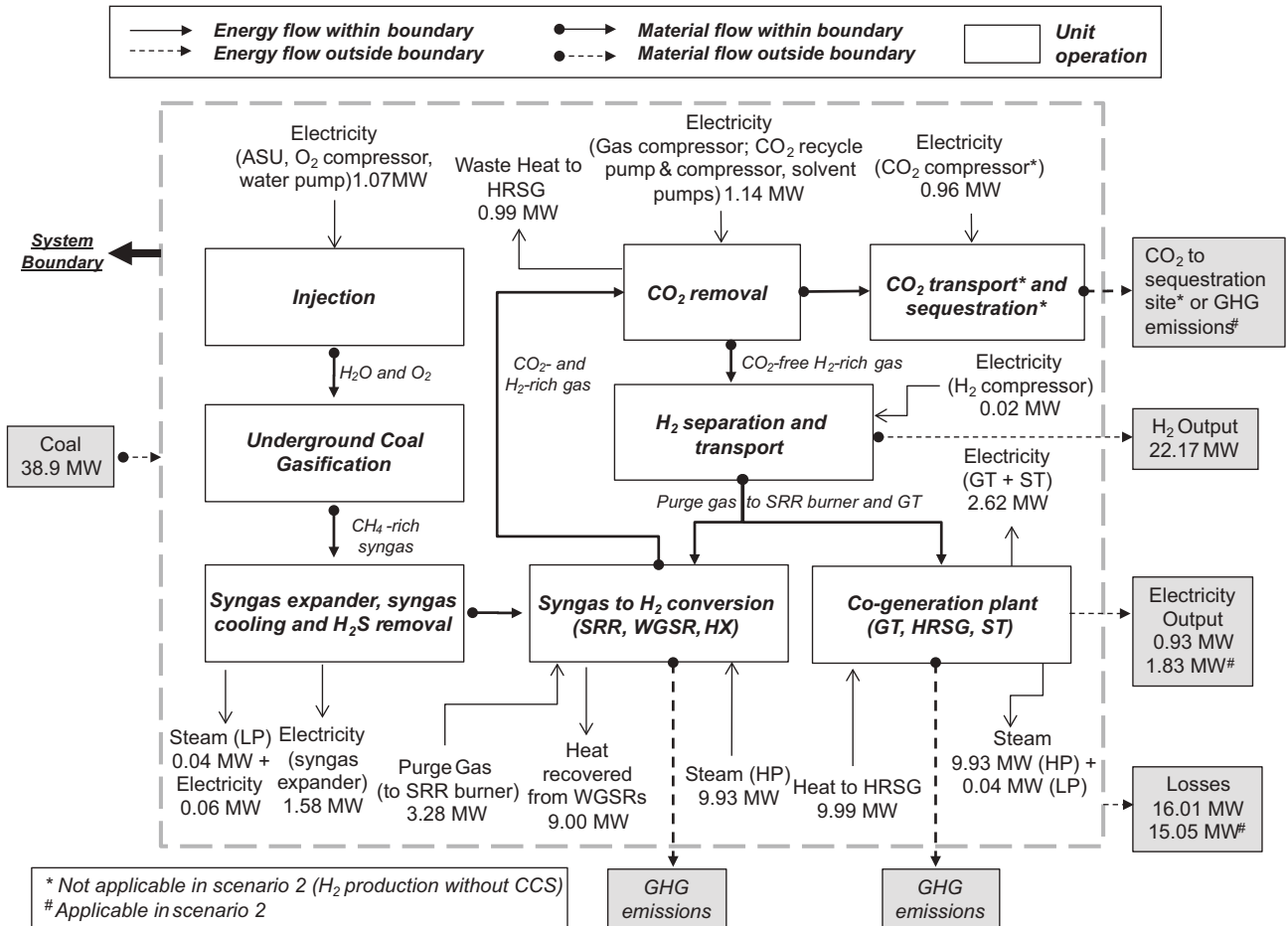


Fig. 5. Energy balance in scenarios 1 and 2 for base case assumptions i.e. total coal input – 118 tonne/day, H₂O-to-O₂ injection ratio – 2 and ground water influx – 0.4 m³/tonne of coal.

moderate effect on the net life cycle GHG emissions. The net life cycle GHG emissions moderately increase in a non-linear fashion with increase in pressure ratio in GT owing to the decreased power output of the GT. Due to reasonable contribution of the CO₂ compressors in the total power consumption (around 30%) in scenario 1, the net life cycle GHG emissions decrease with an increase in the CO₂ compressor efficiency; with an increase in the efficiency, the power consumption decreases, ultimately increasing the net power output and emissions credit for export of electricity to the grid.

The significance of H₂ separation efficiency in the sensitivity analysis is realized on observing a sharp increasing trend in the net life cycle GHG emissions. The observed trend is counter-intuitive as an increase in the H₂ separation efficiency will not only increase the H₂ output but cause a significant decrease in the power output of the GT and the ST. With an increase in the H₂ separation efficiency by 10%, the power output of the GT and ST decreases by 44% and 27%, respectively, and ultimately the emissions credit is reduced by 85%. Overall, the net life cycle GHG emissions increase from 0.91 to 1.50 kg-CO₂-eq/kg-H₂ with an increase in the H₂ separation efficiency in the PSA by 10%. The heat exchanger efficiency also has a major effect on the net cycle GHG emissions, with values increasing by 62.3% upon a drop in the efficiency by 10%. This is mainly due to reduced ST power output in the co-generation plant, eventually resulting in a lower emissions credit. Lastly, GT inlet temperature has a high sensitivity towards the net life cycle GHG emissions. A non-linear decreasing

trend is observed due to low GT power output upon decreasing the GT inlet temperature.

3.3. Net energy ratio (NER)

NER is calculated using Eq. (1). Fig. 5 shows the energy balance for scenarios 1 and 2. This energy balance allows for identification of key energy consumption within and outside the system boundary for scenarios 1 and 2. NER is calculated as 0.59 and 0.61 for scenarios 1 and 2, respectively. The aforementioned NER values indicate that, the aggregate amount of energy extracted from coal is less than the energy content of the coal. This NER also accounts for the energy used in the production of electricity and steam required for operating the H₂ plant in scenarios 1 and 2. Furthermore, the NER in scenario 2 is greater than in scenario 1; this is mainly due to zero energy consumption in CO₂ compression in scenario 2, which ultimately leads to higher electricity export to grid.

3.4. The effect of steam-to-carbon ratio on life cycle GHG emissions

Fig. 6 shows the effect of the steam-to-carbon ratio on the H₂ production and the amount of CO₂ captured in scenario 1. It is important to note that a similar trend is obtained for H₂ production

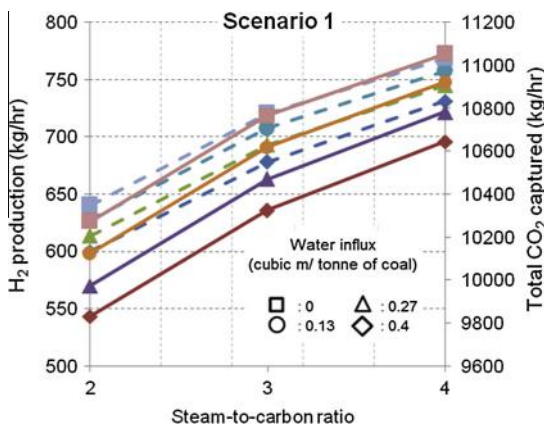


Fig. 6. The effect of the steam-to-carbon ratio on H₂ production and amount of CO₂ captured using Selexol technology in scenario 1 with different ground water influx rates and a fixed H₂O-to-O₂ injection ratio of 2. Dash lines represent H₂ production and solid lines represent total CO₂ captured.

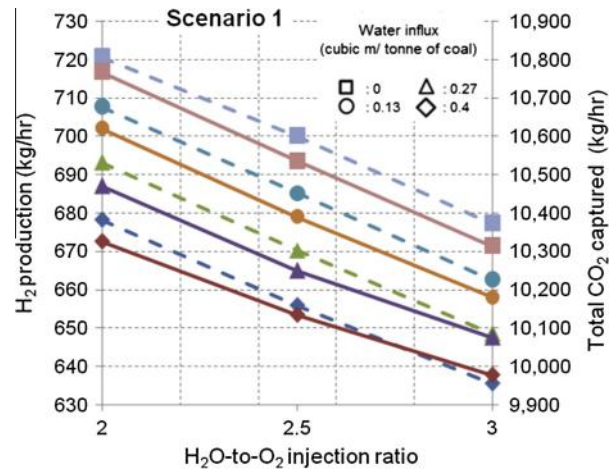


Fig. 8. The effect of the H₂O-to-O₂ injection ratio on H₂ production and amount of CO₂ captured using Selexol technology in scenario 1 with different ground water influx rates, but a fixed steam-to-carbon ratio of 3. Dash lines represent H₂ production and solid lines represent total CO₂ captured.

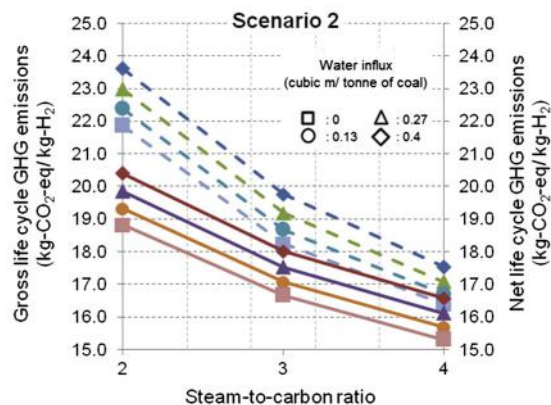
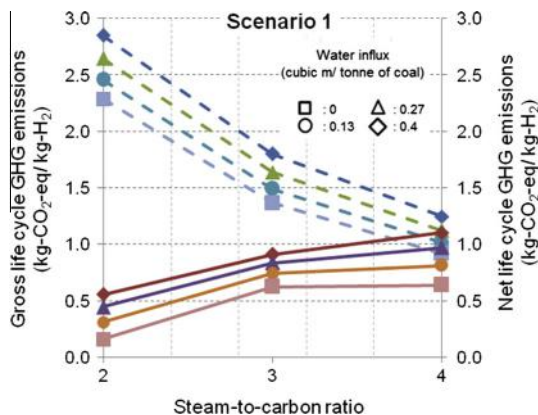


Fig. 7. The effect of the steam-to-carbon ratio on gross and net life cycle GHG emissions in scenarios 1 and 2 with different ground water influx rates, but a fixed H₂O-to-O₂ injection ratio of 2. Dash lines represent gross life cycle GHG emissions and solid lines represent net life cycle GHG emissions.

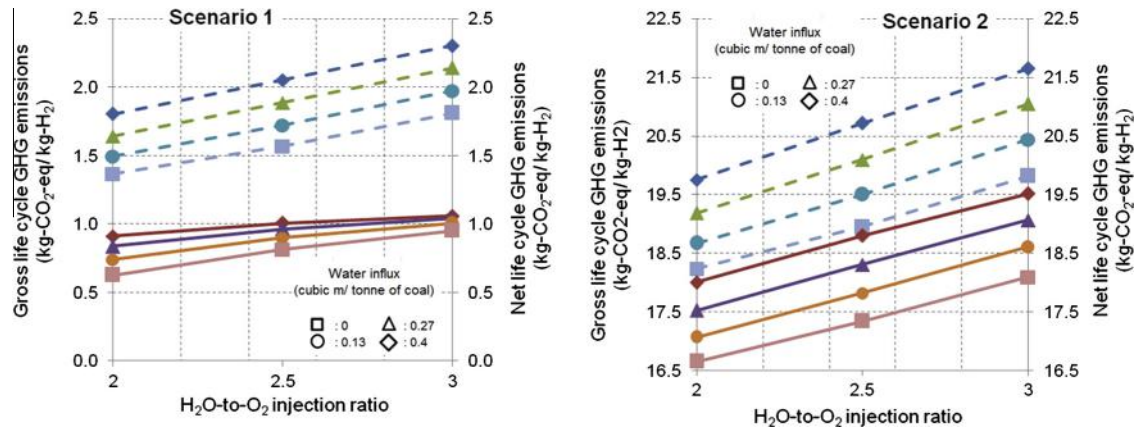


Fig. 9. The effect of the H₂O-to-O₂ injection ratio on gross and net life cycle GHG emissions in scenarios 1 and 2 with different ground water influx rates, but a fixed steam-to-carbon ratio of 3. Dash lines represent gross life cycle GHG emissions and solid lines represent net life cycle GHG emissions.

in scenario 2 because the unit operations up to H₂ production are the same in both scenarios. For a fixed steam-to-carbon ratio, H₂ production falls slightly with increase in ground water influx (see Fig. 6). The reason is two-fold. First, H₂ content in the syngas from UCG falls, while CH₄ content rises [33]. Second, steam consumption in the SRR unit increases to maintain a fixed steam-to-carbon ratio; this makes up for the deficit in H₂ content in the syngas by converting CH₄ into H₂ in the SRR unit [33]. In addition, the amount of CO₂

captured also falls with an increase in ground water influx. Ultimately, an increasing trend of the gross and net life cycle GHG emissions in both scenarios is seen with increase in ground water influx (see Fig. 7).

The effect of the steam-to-carbon ratio can be appreciated over gross and net life cycle GHG emissions in both scenarios (see Fig. 7). With a rise in the steam-to-carbon ratio, H₂ production increases; this stems from the fact that an augmented flow of steam will favor CH₄ conversion into H₂ in the SRR unit. At the same time, increased CH₄ conversion also escalates the amount of CO₂ in the reformed syngas post SRR and WGSR units, the effect of which is eventually realized in improved CO₂ capture. However,

Table 7

Life cycle GHG emissions in different unit operations of H₂ production with and without CCS. The results are presented for the base case of an H₂O-to-O₂ injection ratio of 2, steam-to-carbon ratio of 3 and ground water influx of 0.4 m³/tonne-coal.

Parameter	Values (kg-CO ₂ -eq/kg-H ₂)	
	Scenario 1	Scenario 2
<i>Operation emissions</i>		
Emissions from the CO ₂ removal section	0	17.998
Purge gas combustion ^a	1.521	1.521
Electricity use in H ₂ production	0	0
Electricity use in H ₂ pipeline transport ^b	0	0
Electricity use in CO ₂ pipeline transport ^c	0	–
<i>Non-operation emissions</i>		
Drilling of injection and production well in UCG	0.001	0.001
Drilling and leakage in EOR	0.001	–
CO ₂ pipeline construction	0.038	–
H ₂ pipeline construction	0.193	0.193
H ₂ production plant construction ^d	0.048	0.040
Emissions credit for electricity supply to grid	0.890	1.750
Gross life cycle GHG emissions	1.801	19.752
Net life cycle GHG emissions	0.912	18.003

^a This value represents emissions associated with combustion of purge gas both in the GT and the burner of the SRR unit.

^b Inlet compressor power requirement for H₂ pipeline transport to the bitumen upgrading site is calculated based on the method discussed in Section 2.2.4. This takes into account the pressure losses during pipeline operation without any additional compression. Since, the in-house co-generation plant satisfies the electricity consumed by the inlet compressor, there are no GHG emissions associated with electricity use in both scenarios.

^c CO₂ is compressed to 15 MPa (above its supercritical pressure). The in-house co-generation plant satisfies the electricity consumed by the compressors. This negates the GHG emissions associated with electricity use. Moreover, there is no additional electricity consumption during the operation of CO₂ pipeline to the sequestration site. In order to account for the pressure losses during the operation, calculation of appropriate pipeline diameter is done using the method discussed in Section 2.2.3.

^d The GHG emissions associated with H₂ production plant construction in scenario 1 are slightly higher than in scenario 2 because of additional equipment emissions associated with CO₂ compressors required for CO₂ pipeline operation in scenario 1.

Table 8

Description of various H₂ production pathways considered in a comparative analysis of life cycle GHG emissions.

Pathway Number	Pathway description	Source
Pathway 1	Water electrolysis using electricity generated by wind turbines	[10]
Pathway 2	Integrated photo voltaic system	[7]
Pathway 3.1	Water electrolysis using electricity generated by a hydro plant	[10]
Pathway 3.2	Water electrolysis using electricity generated by a hydro plant	[7]
Pathway 4.1	SCG without co-generation	[3]
Pathway 4.2	SCG with co-generation	[7]
Pathway 4.3	SCG with electricity co-production	[3]
Pathway 4.4	SCG with steam co-production	[3]
Pathway 5.1	SCG-CCS without co-generation	[3]
Pathway 5.2	SCG-CCS with electricity co-production	[3]
Pathway 5.3	SCG-CCS with steam co-production	[3]
Pathway 6.1.1	SMR without co-generation	[9]
Pathway 6.1.2	SMR without co-generation	[10]
Pathway 6.1.3	SMR without co-generation	[8]
Pathway 6.1.4	SMR without co-generation	[3]
Pathway 6.2	SMR with co-generation	[7]
Pathway 6.3	SMR with electricity co-production	[3]
Pathway 6.4.1	SMR with steam co-production	[11]
Pathway 6.4.2	SMR with steam co-production	[3]
Pathway 7.1	SMR-CCS	[8]
Pathway 7.2	SMR-CCS without co-generation	[3]
Pathway 7.3	SMR-CCS with electricity co-production	[3]
Pathway 7.4	SMR-CCS with steam co-production	[3]
Pathway 8	UCG with co-generation	Present model
Pathway 9	UCG-CCS with co-generation	Present model

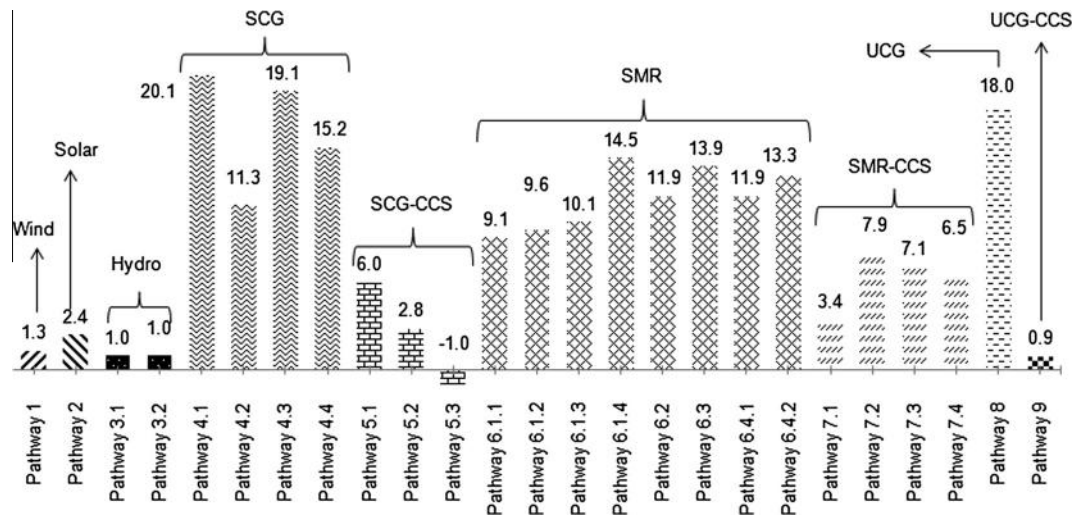


Fig. 10. Comparative analysis of net life cycle GHG emissions in various H₂ production pathways. Pathways 1–3 are renewable energy-based, while pathways 4–9 are fossil-fuel based H₂ production pathways.

the percentage increase in H₂ production (13%) is greater than the percentage increase in CO₂ captured or vented (5%) in both scenarios. As a result, gross life cycle GHG emissions drop with a rise in steam-to-carbon ratio in both scenarios.

Contrastingly, the effect of the steam-to-carbon ratio on the net life cycle GHG emissions is not straight forward in either scenario. With an increase in the steam-to-carbon ratio, an increasing trend is observed in the net life cycle GHG emissions in scenario 1, as compared to a decreasing trend in scenario 2. With a rise in the steam-to-carbon ratio from 2 to 4, net life cycle GHG emissions reduce from 20.38 to 16.57 kg-CO₂-eq/kg-H₂ in scenario 2, while it increases from 0.56 to 1.10 kg-CO₂-eq/kg-H₂ in scenario 1. The reason for the observed trends is multifold. First, with an increase in the steam-to-carbon ratio, the GT power output decreases; due to decreased CH₄ flow in the purge gas, the calorific value of the purge gas falls, which results in lower GT power output for a higher steam-to-carbon ratio. Second, a penalty is enforced on the output of the ST because of rise in steam consumption in the SRR unit. Third, there is an increased energy penalty in capture and compression of CO₂ in scenario 1; the CO₂ content of the syngas after its processing in SRR and WGSRs increases with increase in steam-to-carbon ratio (see Fig. 6).

These three factors (drop in power output of ST and GT, and energy penalty for CCS) result in lower net power output for a higher steam-to-carbon ratio. Eventually, the emissions credit for the export of electricity to the grid declines with a rise in the steam-to-carbon ratio. Since the values of gross life cycle GHG emissions in scenario 1 are much lower than in scenario 2 (see Fig. 7), the effect of the emissions credit on net life cycle GHG emissions is greater in scenario 1 relative to scenario 2. A marginal increasing trend in net life cycle GHG emissions is therefore, achieved in scenario 1 compared to a significant decreasing trend in scenario 2 with increase in steam-to-carbon ratio.

3.5. The effect of the H₂O-to-O₂ injection ratio on life cycle GHG emissions

Fig. 8 shows the effect of the H₂O-to-O₂ injection ratio on the H₂ production output and the total CO₂ captured for a fixed steam-to-carbon ratio of 3. Clearly, both output variables have great sensitivity towards the H₂O-to-O₂ injection ratio; with an increase in H₂O-to-O₂ injection ratio from 2 to 3, the H₂ output and the flow rate of captured CO₂ decrease by around 3.4% and 6.3%, respectively.

This trend is mainly attributable to an increase in CH₄ content, while a decrease in H₂ flow in the syngas after UCG is observed [33].

The effect of the H₂O-to-O₂ injection ratio is clearly transferred to the gross life cycle GHG emissions in scenarios 1 and 2 (see Fig. 9). The decrease in flow of “captured CO₂” results in an increase in CO₂ content of the purge gas. This combined effect of a rise in CO₂ content of purge gas and fall in H₂ output, H₂ production output, eventually increases the gross life cycle GHG emissions from 1.8 to 2.3 kg-CO₂-eq/kg-H₂ in scenario 1 and 19.75 to 21.65 kg-CO₂-eq/kg-H₂ in scenario 2, with rise in the H₂O-to-O₂ injection ratio from 2 to 3. Contrastingly, the increase in net life cycle GHG emissions is marginal in scenario 1. This is mainly because the GHG emissions credit award for increased power output compensates for decreased flow of “captured CO₂” in scenario 1.

4. Comparative assessment with other studies and GHG mitigation potential

This section compares life cycle GHG emissions in H₂ production from UCG-CCS with other H₂ production pathways. H₂ production from UCG-CCS is found to be more environmentally competitive than H₂ production without CCS. The competitiveness of H₂ production from UCG in terms of GHG emissions can be appreciated when the life cycle GHG emissions are compared with other H₂ production pathways. For the comparative assessment, a number of fossil fuel and renewable energy based H₂ production pathways are considered; they are listed in Table 8. Clearly, a wide range of scenarios is present in SCG and SMR, with regards to different plant configurations and schemes (with or without co-generation, only electricity co-production and only steam co-production).

Fig. 10 shows a comparison of life cycle GHG emissions between UCG, SCG, SMR, wind, hydro, and solar energy based H₂ production pathways. It is evident from Fig. 10 that there exists a wide range of values for life cycle GHG emission in the literature for SCG and SMR. This might be due to the consideration of a different system boundary, coal composition, set of assumptions, jurisdiction, etc. ⁹

⁹ These reasons can also be used to explain higher value of net life cycle GHG emissions in H₂ production from UCG without CCS than some reported values in the literature for SCG-based H₂ production pathway without CCS (see Fig. 10). To put this into perspective, the emissions associated with electricity production from UCG are evaluated to be 0.843 tonnes-CO₂-eq/MWh as compared to 0.88 tonnes-CO₂-eq/MWh from SCG in Alberta (see Table 6).

For example, in pathway 7.1 [8], amine absorption technology is utilized for CO₂ capture (with 85% efficiency); additional steam and electricity use (other than in H₂ production) for CCS system is derived from electricity producing NGCC–CCS plant. Moreover, the authors assume CO₂ compression pressure of 13.5 MPa for its transport to a storage site via a 300 km pipeline. Equipment emissions associated with CCS system are considered and no credits are awarded for steam additional steam produced by the system. In comparison, the LCA model discussed in [3] uses default values for estimating the energy consumption in CCS (pathways 7.2–7.4 and 5.1–5.3) without explicitly stating the CO₂ capture technology, underlying process assumptions and associated equipment emissions. The pathways with electricity co-production (4.3, 5.2, 6.3 and 7.3) have greater GHG footprint than with steam co-production counterpart (4.4, 5.3, 6.4.2 and 7.4, respectively). This is mainly because the emissions credit awarded for electricity export in the former cases is higher than for steam export in the latter cases.

The UCG–CCS pathway has a significantly lower GHG footprint than other fossil fuel based H₂ production pathways for all plant configurations, except SCG–CCS with steam co-production. The advantage of integrating CCS technology with UCG can be realized as this pathway becomes competitive with even renewable energy-based H₂ production pathways – wind, solar and hydro. To put this into perspective, if H₂ were produced from UCG–CCS instead of the predominant SMR process, nearly 15.3 Mt of GHG emissions would be mitigated per year in the bitumen upgrading industry of Alberta in 2022. This GHG abatement potential is calculated based on SCO production of 0.20 million m³/day in 2022 [4], H₂ requirement of 2.52 GJ–H₂/m³–SCO [3] and an average value of life cycle GHG emissions (around 10.8 kg–CO₂–eq/kg–H₂) for SMR-based pathway without CCS reported by authors in [7–11]. With that said, large-scale implementation of UCG–CCS technology still remains a challenge in order to gain the environmental advantages over other pathways, especially SMR, for H₂ production. Some of the challenges to implement UCG technology include low process control, lack of consistency of syngas quality and composition, and other associated environmental risks e.g., ground water contamination and land subsidence [6]. Furthermore, low natural gas prices decrease the economic competitiveness of producing H₂ from UCG technology as compared to SMR technology, especially in western Canada [6].

5. Conclusion

This paper examined life cycle GHG emissions of H₂ production from UCG for two scenarios with and without CCS by developing the FUNNEL–GHG–H₂–UCG. The net life cycle GHG emissions are estimated to be 0.91 and 18.00 kg–CO₂–eq/kg–H₂ in H₂ production from UCG with and without CCS, respectively. Adoption of CCS technology leads to a substantial reduction in total life cycle emissions in H₂ production from UCG. Purge gas combustion and venting of gases in the CO₂ removal section are the major contributing factors in the net life cycle GHG emissions. On the other hand, energy and material use in drilling, H₂ and CO₂ pipeline transportation, and other construction contributed around 15.6% and 1.2% towards life cycle GHG emissions in H₂ production with and without CCS, respectively.

Furthermore, the net life cycle GHG emissions increase marginally with a rise in the H₂O-to-O₂ injection ratio and the steam-to-carbon ratio in H₂ production from UCG with CCS. In addition, the sensitivity analysis showed that the net life cycle GHG emissions are most sensitive to the separation efficiency of the PSA and the efficiency of the heat exchanger. The net energy ratios were estimated to be 0.59 and 0.61 in H₂ production with and without CCS, respectively.

UCG–CCS is found to have a lower life cycle GHG emissions footprint in comparison to other conventional H₂ production pathways (SCG, SCG–CCS, SMR and SMR–CCS); only exception being SCG–CCS with steam co-production. UCG–CCS based H₂ is also comparable with wind, hydro, and solar based H₂ in terms of GHG emissions. If the traditional SMR process is replaced by UCG–CCS process for H₂ production in the bitumen upgrading industry, a reduction of around 15.3 Mt in GHG emissions can be achieved in 2022.

Acknowledgments

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