A Comparative Life Cycle Assessment of Hydrogen Production in British Columbia

by

ALISA HOLTZ

A Thesis Submitted to the Faculty of Social and Applied Sciences
in Partial Fulfilment of the Requirements for the Degree of

MASTER OF SCIENCE IN ENVIRONMENT AND MANAGEMENT

Royal Roads University
Victoria, British Columbia, Canada

Supervisor: CHRIS LING
JULY, 2021

COMMITTEE APPROVAL

The members of Alisa Holtz’s Thesis Committee certify that they have read the thesis titled A Comparative Life Cycle Assessment of Hydrogen Production in British Columbia and recommend that it be accepted as fulfilling the thesis requirements for the Degree of MASTER OF SCIENCE IN ENVIRONMENT AND MANAGEMENT:

CHRIS LING [signature on file]

MATT DODD [signature on file]

Final approval and acceptance of this thesis is contingent upon submission of the final copy of the thesis to Royal Roads University. The thesis supervisor confirms to have read this thesis and recommends that it be accepted as fulfilling the thesis requirements:

CHRIS LING [signature on file]

Creative Commons Statement

Abstract

Hydrogen can play a key role in decarbonizing energy systems and the transition to a low carbon economy. While scaling up hydrogen production plays a critical role in initiating a hydrogen economy, it is also important to quantify the environmental impacts to determine what pathways will adequately contribute to emission reduction goals. To assess these impacts, a comparative well-to-gate life cycle assessment (LCA) was performed to determine the carbon intensity of three hydrogen production pathways in British Columbia (B.C.) using the *GHGenius* 4.03a software model. The hydrogen production pathways reviewed include steam methane reformation (SMR), SMR with carbon capture and storage, and electrolysis using the B.C. grid electricity mix. The LCA results were 82.75, 26.07, and 24.42 g CO_2e/MJ HHV respectively. Additional objectives of this study include identifying barriers and recommending policies to increase production of low carbon hydrogen in B.C., and defining a carbon intensity benchmark.

Table of Contents

Creative Commons Statement ... 3
Abstract ... 4
Table of Contents ... 5
List of Tables ... 7
List of Figures ... 7
Acknowledgements ... 8
Introduction ... 9
  Research Question and Objectives ... 12
Literature Review ... 12
  Global Hydrogen Sources, Volumes, and Uses ... 12
  Selection of Hydrogen Production Methods ... 13
    Steam methane reformation (SMR). ... 13
    SMR with carbon capture and storage (CCS). ... 13
    Electrolysis. ... 14
  Life Cycle Assessment (LCA) ... 14
    LCA rationale. ... 14
    Four stages of an LCA. ... 15
    LCA data sources. ... 16
  Carbon Intensity of Hydrogen ... 18
Policy Frameworks ... 21
  British Columbia ... 22
    Low Carbon Fuel Standard. ... 22
    Greenhouse Gas (Clean Energy) Reduction Regulation. ... 27
  European Union ... 28
    CertifHy. ... 28
Methodology ... 30
  Goal and Scope Definition ... 30
    System boundary. ... 31
    Functional unit. ... 32
    Allocation method. ... 32

Impact Category and Life Cycle Impact Assessment Method 33
Data and Initial Data Quality Requirements 33
Methodological Assumptions 34
Inventory Analysis 36
Scenario 1: Steam methane reforming (SMR). 36
Scenario 2: SMR + carbon capture and storage (CCS). 37
Scenario 3: Electrolysis. 39
Results and Discussion 41
Scenario 1 (SMR) 43
Scenario 2 (SMR + CCS) 44
Scenario 3 (Electrolysis) 45
Uncertainties 47
Barriers to Increasing Low Carbon Intensity Hydrogen Production in B.C. 48
Economic Opportunities and Business Implications 49
Recommendations 51
Establishing a Low Carbon Intensity Hydrogen Benchmark 51
Sensitivity Analysis. 52
Policy Options to Incent Low Carbon Hydrogen Production in B.C. 55
Conclusion 56
References 59
Appendix A: Default *GHGenius* 4.03a Values 66

List of Tables

Table 1 Summary of Hydrogen Carbon Intensity Literature Values 21
Table 2 LCFS Carbon Intensity Reduction Schedule 24
Table 3 LCFS Default Carbon Intensities 26
Table 4 Key LCA Methodological Choices 34
Table 5 Energy Input Values for SMR in 2020 37
Table 6 Energy Input Values for the Carbon Capture Process in 2020 38
Table 7 Energy Input Values for SMR + CCS in 2020 39
Table 8 B.C. Grid Electricity Mix Values in 2020 40
Table 9 Summary of Energy Input Values by Pathway in 2020 40
Table 10 LCA Carbon Intensity Results (g CO_2e/GJ) 42
Table 11 Summary of Carbon Intensities from SMR-derived Hydrogen 43
Table 12 Summary of Carbon Intensities from SMR + CCS-derived Hydrogen 45
Table 13 Summary of Carbon Intensities from Electrolytic Hydrogen 46
Table 14 Scenario 1 Baseline SMR Carbon Intensity and 60% reduction 52
Table 15 Carbon Intensity of SMR + CCS with 50 – 98% Carbon Capture Rates 54
Table 16 Default GHGenius 4.03a SMR Input Values in 1996 66
Table 17 Default GHGenius 4.03a Hydrogen Values in 2000 (Alt Fuels Prod Sheet) ... 66
Table 18 GHGenius 4.03a Emission Factors in 2020 67

List of Figures

Figure 1 Life Cycle Assessment Framework 31
Figure 2 System Boundary of SMR Pathway 36
Figure 3 System Boundary for SMR + CCS Pathway 37
Figure 4 System Boundary for Electrolysis Pathway 39

Acknowledgements

I acknowledge, with gratitude and respect, the Lekwungen peoples on whose traditional territory I live, and the relationships of the Songhees, Esquimalt, and W̱SÁNEĆ peoples with this land, its laws, and their languages that continue to this day. I also thank the Kwakiutl peoples on whose lands I was born and raised, and who have taught me so much.

To my supervisor, Dr. Chris Ling, I express my sincere gratitude for your valuable support and guidance throughout this journey. To my committee member, Dr. Matt Dodd, thank you for your support and helpful comments during the final stages of my thesis. To the Natural Sciences and Engineering Research Council of Canada (NSERC), the Government of British Columbia, and Royal Roads University, thank you for providing the financial support to allow me to continue my education.

Additionally, I would like to thank Dr. Guy Gensey who inspired my thesis topic. Thank you for your support and guidance, I will be forever grateful. To Dr. Michael Rensing, thank you for listening and taking the time to bounce ideas around. To Don O’Connor, thank you for your technical expertise and availability throughout the writing process.

A special thank you to my parents, without your lifelong support and belief in me, I wouldn’t be where I am today. To my dad, for saying “there’s never a bad time for education”, and to my mom, for the countless hours of babysitting so that I could complete my assignments.

And finally, thank you to my family. To my children, Marcus and Abigail, thank you for your understanding and patience, and for representing the future generations who will hopefully benefit from a low carbon economy. And finally, to my husband Greg, who always inspired me to achieve my goals and whose love and support I could not have done this without.

Introduction

This study researches the carbon intensity of three hydrogen production methods in British Columbia (B.C.) using a comparative life cycle assessment (LCA) and the *GHGenius* 4.03a software model. The hydrogen production pathways reviewed include steam methane reformation (SMR), SMR with carbon capture and storage (CCS), and electrolysis using the B.C. low carbon grid electricity mix. Objectives of the study include determining the production pathway with the lowest carbon intensity, identifying barriers and recommending policies to increase the production of hydrogen, and proposing a carbon intensity benchmark.

Hydrogen can play a key role in decarbonizing energy systems. As global energy consumption is expected to increase, driven by rising standards of living and a growing population, hydrogen is an attractive candidate as a sustainable energy source (Bhandari, Trudewind, & Zapp, 2013). "It can be produced using renewable energy resources; has high yields in fuel cells; undergoes clean combustion without emissions of carbon dioxide (CO_2) and oxides of nitrogen and sulfur (NO_x, SO_x); and makes indirect storage of the intermittent renewable energy resources feasible" (Bhandari et al., 2013, p.1). "Hydrogen holds the potential to decarbonize many sectors of our economy, including transportation, power production and storage, heat for industry and buildings, feedstock, and export" (Natural Resources Canada [NRCan], 2020, p. 15).

According to the International Energy Agency (IEA), global transportation emissions have continued to increase 1.9 % annually since 2000 (IEA, 2020). This is in part due to a growing global middle class which are travelling more (with exception to the COVID-19 pandemic) and shipping more goods. In Canada, the transportation sector accounts for 24% of national greenhouse gas (GHG) emissions, mostly from freight trucks and passenger vehicles

(Environment and Climate Change Canada, 2017). In B.C., the transport sector accounts for 39% of provincial emissions, with more than half being emitted from medium and heavy-duty transportation vehicles (Provincial Inventory, 2015). This is due to almost all (95%) of the world's transportation energy coming from petroleum-based fuels, largely gasoline and diesel, which when combusted, emit CO_2 (United States Environmental Protection Agency, 2021, para. 8).

Hydrogen can play a role in decarbonizing the transportation sector when used directly in hydrogen fuel cell electric vehicles, which emit zero carbon emissions. Approximately 89% of emissions are reduced per kilometer (km) when low carbon hydrogen (90% carbon capture) is used to replace gasoline in an internal combustion engine vehicle and approximately 83% of emissions are reduced per km when replacing diesel (Layzell, Young, Lof, Leary & Sit, 2020).

Hydrogen is also used to refine fossil fuels and in the production of synthetic fuels such as renewable diesel, as large quantities of hydrogen are required by the refining process. “Transport is seen as the key field of application for hydrogen because of the need for low-carbon fuels to gradually replace conventional fuels and thereby minimise life cycle emissions over the supply chain” (Valente, Iribarren, & Dufour, 2017, p.347). In 2014, an estimated 168.7 megatonnes (Mt) of GHG emissions were reduced globally due to the use of biofuels, with Canada achieving 2.6 Mt of reductions through the consumption of 2095 million litres of biofuel ($S\&T^2$ Consultants Inc., 2015). Increased production and use of low carbon fuels represents a key sustainable development opportunity to decarbonize the transportation sector and mitigate climate change.

The B.C. Hydrogen Study (2019) estimated hydrogen has the potential to reduce the province’s emissions by 15.7 Mt per year by 2050 in a best-case scenario. This is because hydrogen as is a versatile energy carrier with many end use applications. Since B.C. has an abundance of hydroelectricity, the focus for hydrogen use in B.C. is in applications where electrification is not feasible, such as the hard-to-abate sectors of long-distance transportation (e.g., heavy-duty trucking, marine, aviation), in heating applications and industrial processes.

In the built environment, hydrogen can be injected into the natural gas distribution system to lower the overall carbon intensity of the gas combusted, providing environmental advantages to fossil fuel combustion. Layzell et al. (2020), reported a 67% reduction in life cycle GHG emissions when low carbon hydrogen replaced natural gas for space and water heating. Industrial applications use hydrogen as a feedstock in ammonia, steel and methanol production to displace coal and natural gas (NRCan, 2020). In a best-case scenario, hydrogen use across Canada is forecasted to contribute 190 Mt of annual GHG reductions by 2050 (NRCan, 2020).

To address emissions, governments around the world are implementing policies and regulations e.g., adopting net zero by 2050 emissions targets and becoming Paris Agreement signatories. In B.C., the government is investing in cleaner fuels, and accelerating their deployment through policy adoption e.g., B.C.'s Low Carbon Fuel Standard and the Greenhouse Gas (Clean Energy) Reduction Regulation. In December 2018, the B.C. government released its CleanBC climate action plan focusing on reducing GHGs through increasing electrification, energy efficiency and the production of low carbon fuels.

While scaling up hydrogen production plays an essential role in initiating B.C.'s hydrogen and low carbon economies, it is also important to quantify the environmental impacts to determine what pathways will adequately contribute to GHG reduction goals. The information provided by this study will help industry and policy makers as they continue working towards increasing the production of low carbon fuels in B.C. and the transition to a low carbon economy.

Research Question and Objectives

Research Question: Which hydrogen production method results in the lowest carbon intensity on a life cycle basis?

Objective 1: Determine the carbon intensity of hydrogen produced by three methods in B.C.: steam methane reformation (SMR); SMR with carbon capture and storage (CCS); and by electrolysis using B.C.'s low carbon grid electricity mix.

Objective 2: Identify barriers and recommend policies to increase the production of low carbon hydrogen in B.C.

Objective 3: Define a carbon intensity benchmark for fossil fuel-derived hydrogen.

Literature Review

The literature review begins by providing background information on global hydrogen sources, volumes and uses, and a description of the three hydrogen production methods studied. An overview of the LCA process follows as well as rationale for its choice as the method of analysis. Lastly, details of the literature reviewed related to the carbon intensity of hydrogen are summarized.

Global Hydrogen Sources, Volumes, and Uses

Hydrogen can be extracted from fossil fuels, biomass or water (IEA, 2019). In 2019, global hydrogen production was approximately 70 Mt with the vast majority (76%) using natural gas as a feedstock and the remainder (23%) using coal (IEA, 2019). Most hydrogen in the world is used in petroleum refineries to produce diesel and, to a lesser extent, renewable diesel. The second largest global usage of hydrogen is in fertilizer (ammonia) production. Hydrogen production from fossil fuels e.g., natural gas, releases CO_2 to the atmosphere which contributes to adverse environmental impacts, such as global warming and climate change. Hydrogen produced from natural gas generates approximately 10 tonnes of CO_2 per tonne of hydrogen (IEA, 2019).

Selection of Hydrogen Production Methods

Steam methane reformation (SMR).

SMR is a mature technology and the most widespread method of producing "*grey*" hydrogen – hydrogen produced from non-renewable energy (IEA, 2019). This process adds hot steam to methane gas which produces a synthesis gas of carbon monoxide and hydrogen, see Equation 1. Then in a water-gas shift reaction, carbon monoxide is reacted with steam to produce carbon dioxide and more hydrogen, see Equation 2. Lastly, purification is performed, commonly using a pressure swing adsorption (PSA) unit to remove carbon dioxide and other impurities from the gas stream leaving highly concentrated hydrogen (Spath & Mann, 2001).

Steam-methane reforming reaction

$$CH_4 + H_2O\ (+\ heat) \rightarrow CO + 3H_2 \tag{1}$$

Water-gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2\ (+\ small\ amount\ of\ heat) \tag{2}$$

SMR with carbon capture and storage (CCS).

In an SMR plant, CO_2 can be separated from the high-pressure synthesis gas stream, reducing emissions by 60% and subsequently captured from the more diluted furnace flue gas, boosting the overall emissions reductions to 90% (IEA, 2019). Once separated, the CO_2 can be permanently stored deep underground in geological formations or used in industrial processes e.g., enhanced oil recovery (EOR). Hydrogen produced from SMR + CCS is commonly termed "*blue*" hydrogen.

Electrolysis.

Electrolysis currently accounts for about 2% of global hydrogen production (IEA, 2019). Water electrolysis is a process whereby water splits into hydrogen and oxygen through the application of electrical energy (Bhandari et al., 2013). The cells are connected in parallel to form the electrolyzer module and the hydrogen and oxygen generated are cooled, purified, compressed, and stored (Bhandari et al., 2013). Hydrogen produced by electrolysis using renewable sources such as hydroelectricity is commonly termed "*green*" hydrogen.

Life Cycle Assessment (LCA)

The LCA approach is a well-established methodology for the comprehensive evaluation of the potential environmental impacts of product systems (Valente et al., 2017). An LCA is an effective tool for analyzing a wide range of environmental impacts from all phases of industrial activity (Zhao & Pedersen, 2018). The LCA process compiles an inventory of relevant energy and material inputs and environmental releases, evaluates the potential environmental impacts, and interprets results to help decision makers identify levers to reduce impacts and make more informed decisions (Bhandari et al., 2012).

LCA rationale.

Most researchers using the LCA approach rely on its international acceptance and use. An LCA is an established and internationally accepted methodology that is defined by the International Standards Organization (ISO) standards: 14040 and 14044 (Bhandari et al., 2012). The ISO standards provide the framework for LCA analysis while maintaining control of key requirements such as the system boundary and functional unit. In addition, guidelines have been produced e.g., the FC-Hy Guide, providing technical guidance on how to conduct an LCA according to ISO standards for hydrogen production systems (Lozanovski, Schuller & Faltenbacher, 2011).

Four stages of an LCA.

Goal and scope definition.

An LCA has four main stages: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation (Bhandari et al., 2012). The goal and scope definition stage details key aspects such as the functional unit and the system boundary, as well as the objectives and the purpose of the study (Valente et al., 2017). The functional unit provides a reference for relating the inputs and outputs of the systems e.g., travelled distance, mass, or energy (Muresan, Cormos, & Agachi, 2014). Determining the system boundary is very important in a comparative LCA as it ensures comparison of similar life cycle components e.g., storage, distribution, and use (Valente et al., 2017). A full LCA is termed a "cradle-to-grave" assessment because it considers the impact from all stages of a product's life cycle including raw material extraction, fuel production, distribution, storage, dispensing, and end use. LCAs with a well-to-gate system boundary are often referred to as partial LCAs because they do not consider emissions from all stages of the fuel life cycle such as fuel dispensing or end use. In this study, a partial well-to-gate LCA is performed in order to have a common point to compare the three production scenarios modelled. Other LCAs specific to transportation fuels or vehicles are often broken down into two separate system boundaries to better allocate emissions to each stage. These are termed well-to-tank, which includes fuel storage and transport; and tank-to-wheels, which includes dispensing and end use in a vehicle.

Life cycle inventory analysis.

The second stage of an LCA, the inventory analysis, focuses on the compilation and qualification of relevant inputs and outputs associated with the production of the functional unit (Muresan et al., 2014). "The inventory depends on inherent assumptions and the availability of the data" (Scholz & Tietie., 2002, p. 289). Valente et al. (2017) also commented that the quality of the data in the inventory phase significantly affects the reliability of the assessment.

Life cycle impact assessment.

The third stage is the impact assessment which identifies and evaluates the significance of flows traversing the system boundaries and simplifies them into a few key selected environmental areas of interest to systematically evaluate the impacts (Muresan et al., 2014). Examples of impact categories include global warming potential, acidification, eutrophication, primary energy demand (renewable and non-renewable), ozone layer depletion, and human toxicity potential (Lozanovski et al., 2011).

Interpretation and analysis.

Finally, the fourth stage, is the interpretation and analysis of results. In this stage the results of the LCA are evaluated in relation to the defined goal and scope in order to reach conclusions or recommendations (Lozanovski et al., 2011).

LCA data sources.

The main data collection method for an LCA is to use LCA software which includes a database built into the software program. For example, Simons & Bauer (2011) used Ecoinvent, a comprehensive LCA database for industrial processes with specific hydrogen production scenarios determined using SimaPro software. As noted by Nie & Bi (2018), data quality and specificity are critical issues for LCA studies with spatial variation and local environmental uniqueness requiring special attention. In order to improve LCA results, whenever possible, region specific data should be used, otherwise country averages, industry reports or peer-reviewed literature (Nie & Bi, 2018).

> The quality of the data determines the quality of the whole study. In general, there are two types of data used in a LCA study. Primary inventory data is recommended to be used for the main processes, i.e. input and output data of a hydrogen production system. Examples of these would be amount of energy consumed and amount of hydrogen produced. Secondary data will also be needed e.g., the inventory of the electricity consumed in the production of an intermediate material (Lozanovski et al., 2011, p. 47).

There are a number of different LCA models available for use that have been tailored to assess the environmental impact of transportation fuels, each with its own set of data and assumptions. *GHGenius,* which contains B.C. specific fuel data, is the model used in this study. Other models similar to *GHGenius* include the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by the Argonne National Laboratory. GREET is the required model for calculating carbon intensities under California's Low Carbon Fuel Standard. In Europe, the BioGrace model is an approved voluntarily scheme to demonstrate the sustainability of biofuels. Currently, under development is the model required by Environment and Climate Change Canada under the proposed federal Clean Fuel Regulations. This model is expected to be available in December 2021. Using different models with different assumptions, will inevitably lead to different results. Therefore, it is important users have a comprehensive understanding of the model in order to interpret results accurately and make viable conclusions.

Carbon Intensity of Hydrogen

Carbon intensity represents the GHG emissions associated with the life cycle of a fuel. The carbon intensity of hydrogen is commonly expressed in grams of CO_2 equivalent per megajoule (MJ) of energy provided by that fuel, or kg CO_2e per kg hydrogen.

In 2001, Spath and Mann conducted a landmark LCA study for the U.S. National Renewable Energy Laboratory (NREL). Hydrogen production via natural gas reformation was modelled in a full cradle-to-grave LCA including emissions related to natural gas production and distribution, as well as electricity generation. Results indicated an overall global warming potential (GWP) of 11,888 g CO_2e/kg hydrogen on a lower heating value (LHV) basis. Their base case indicated the most significant source of emissions was from the hydrogen plant itself at 74.8%, with emissions from feedstock natural gas production and transport accounting for 25% of total emissions. As expected with SMR technology, Spath and Mann (2001) found CO_2 to be the main contributor (89.3%) of the GWP and methane from natural gas losses during production and distribution was found to contribute 10.6%. Koroneos (as cited in Bhandari et al., 2012) also noted methane emissions from natural gas losses during production and distribution have a large effect on the GWP of the system. A sensitivity analysis showed the hydrogen plant efficiency, changes in natural gas losses, and the hydrogen plant steam balance, all had a significant effect on GWP and the energy balance of the system showed for every 0.66 MJ of hydrogen produced, 1 MJ of fossil energy was consumed (Spath & Mann, 2001).

In 2004, Spath and Mann conducted an LCA of low carbon hydrogen production via electrolysis of wind-derived renewable electricity and found the pathway to have a carbon intensity of 970 g CO_2e/kg hydrogen. Of this, 78% of emissions were accounted to wind turbine production and operation, 4.4% to electrolytic hydrogen production and operation, and 17.6% to hydrogen compression and storage. The average energy requirement, on a LHV basis, was 9.1 MJ/kg hydrogen (72.6% from wind turbines, 31.6% from storage, and 4.8% from electrolysis) (Spath & Mann, 2004). The study concluded most of the resources required, energy consumed, pollutants emitted, and waste generated were due to plant construction (manufacturing and constructing of the wind turbines) and almost no emissions resulted from plant operation (Spath & Mann, 2004).

Bhandari et al. (2012) carried out a literature review of 21 LCA studies focusing on electrolytic hydrogen using renewable electricity. They found most studies analyzed GWP and compared results to conventional production methods e.g., SMR of natural gas. When Bhandari et al. (2012) attempted to compare LCA results from different production pathways, they found it difficult. "Because of differences in system boundary assumptions, different system sizes, different methods used for environmental impact assessment, different functional units and several other such differences, it is difficult to make an accurate and direct comparison of results from one LCA study to the other one" (Bhandari et al., 2012, p. 27). They concluded, "from an environmental analysis perspective, it can be concluded that electrolytic hydrogen production using wind or hydropower generated electricity is one of the best methods for hydrogen production over that from natural gas reforming or electrolysis using the electricity from fossil fuel dominated grids" (Bhandari et al., 2012, p. 2).

In 2013, NREL undertook a comprehensive study of hydrogen production from 10 pathways. Pathway 1, hydrogen from distributed (on-site) SMR of natural gas was most closely aligned with production Scenario 1 of this study. The results indicated a carbon intensity of 136.4 g CO_2e/MJ hydrogen (Ramsden, Ruth, Diakov, Laffen, & Timbario, 2013). This included 19.6 g CO_2e/MJ for natural gas production and delivery (recovery, processing and pipeline transport), 90.7 g CO_2e/MJ for hydrogen production (desulfurization, SMR, water gas shift, and pressure swing adsorption), and 26.1 g CO_2e/MJ for forecourt distribution (compression, gaseous hydrogen storge and dispensing) (Ramsden et al., 2013, p. 36).

In 2019, the IEA published a comprehensive report titled "The Future of Hydrogen" which includes a summary of carbon intensities for hydrogen from various pathways including SMR, SMR + 56% CCS, SMR + 90% CCS, and from renewable electricity. The results were approximately 8.5, 4, 2, and 0 kg CO_2e/ kg hydrogen, respectively (IEA, 2019). The carbon intensities did not include CO_2 emissions from transmission and distribution of the fuel.

Antonini et al. (2020) summarized total GHG emissions for natural gas configurations with CCS ranging between 22 and 48 g CO_2e/MJ LHV and approximately 90 g CO_2e/MJ if no CCS is added to the hydrogen plant.

Layzell et al. (2020), reported emissions of 9 kg CO_2e/kg hydrogen produced by steam methane reformation of natural gas. They also noted another 1.72 kg CO_2e/kg hydrogen associated with upstream natural gas recovery and infrastructure emissions. Hydrogen produced via SMR + CCS resulted in net production emissions of 0.97 kg CO_2e/kg hydrogen (assuming a 90% capture rate), plus upstream infrastructure emissions of 1.84 kg CO_2e/kg hydrogen, resulting in total emissions of 2.8 kg CO_2e/kg hydrogen (Layzell et al., 2020). According to Layzell et al. (2020), life cycle emissions associated with hydrogen production via electrolysis using large-scale hydro, were about 1 kg CO_2e/kg hydrogen. Lastly, they state 'if the goal is to encourage the production and use of energy carriers that have very low or zero GHG emissions, classifying the 'colours' of hydrogen should be replaced by a classification system that is based on the life cycle carbon intensity" (Layzell et al., 2020, p.31). A summary of hydrogen carbon intensity literature values is presented in Table 1.

Table 1

Summary of Hydrogen Carbon Intensity Literature Values

Reference	**Carbon Intensity** *(kg CO_2e/kg H_2)*	**Comments**
SMR-derived Hydrogen		
Antonini et al. (2020)	10.8	90 g CO_2e/MJ
Bhandari et al. (2012)	8.9 – 12.9	
CertifHy (2019a)	10.9	36.4 g CO_2e/MJ, LHV
IEA (2019)	8.5	Fuel transmission and distribution not included
Layzell et al. (2020)	10.72	
Ramsden et al. (2013)	13.23	Fuel compression, storage and dispensing not included
Spath & Mann (2001)	11.9	
SMR + CCS-derived Hydrogen		
Antonini et al. (2020)	2.64 -5.76	22 – 48 g CO_2e/MJ, LHV
CertifHy (2019a)	4.37	LHV, 60% reduction from SMR baseline
IEA (2019)	4	56% carbon capture, fuel transmission and distribution not included
IEA (2019)	2	90% carbon capture, fuel transmission and distribution not included
Layzell et al. (2020)	2.8	90% carbon capture
Electrolytic Hydrogen Derived from Renewable Sources		
Bhandari et al. (2012)	4.1	Green
Bhandari et al. (2012)	2.4	Wind
IEA (2019)	0	Renewable, fuel transmission and distribution not included
Layzell et al. (2020)	1	Large hydro
Spath & Mann (2004)	0.97	Wind, cradle-to-grave

Policy Frameworks

This section provides an overview of existing policy frameworks in B.C. related to climate targets and potentially, hydrogen production. Then an overview of the European

Union's (EU) CertifHy framework for the generation of guarantees of origin (GOs) for green and low carbon hydrogen is provided.

British Columbia

B.C. has set ambitious GHG emission reduction targets of 40% by 2030, 60% by 2040, and 80% by 2050, relative to 2007 levels. To achieve these targets a number of policy measures have been implemented including carbon pricing, a Low Carbon Fuel Standard, and in late 2018, the release of CleanBC, the Province's climate action plan. CleanBC committed to a 20% reduction in the carbon intensity of fuels used in B.C. by 2030 and an increase in the production of renewable fuels in B.C. to 650 million litres. In addition to these policies and commitments, there are a number of provincial funding programs aimed at reducing emissions and driving low carbon technology adoption (e.g., the CleanBC Industry Program, Go Electric Program, Innovative Clean Energy Fund, and the CleanBC Industrial Electrification Rate).

However, existing polices and programs are insufficient to overcome the high cost of implementing innovative technologies (i.e., low carbon hydrogen), and transitioning to a low carbon economy in the timeframes required to limit global warming to 2 degrees, and preferably 1.5 degrees as recommended by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2018). In order to incent the production of low carbon hydrogen, government support will be required. Two B.C. specific policies, the Low Carbon Fuel Standard and the Greenhouse Gas (Clean Energy) Reduction Regulation, are explored further as potential mechanisms to incent the production of low carbon hydrogen.

Low Carbon Fuel Standard.

The *Greenhouse Gas Reduction (Renewable and Low Carbon Fuel Requirements) Act* and the Renewable and Low Carbon Fuel Requirements Regulation, known collectively as

B.C.'s Low Carbon Fuel Standard (LCFS), came into effect in 2010. Its objectives are to reduce reliance on non-renewable fuels, reduce the environmental impacts of transportation fuels, and spur growth in the clean fuels industry in B.C. ("B.C. LCFS Requirements", n.d., para. 1). The province is one of a few jurisdictions in the world that has implemented an LCFS. The LCFS is frequently compared to the well-established California LCFS and the newly proposed Canadian national Clean Fuel Standard which is under development by the federal government.

The LCFS achieves its objectives with two main requirements. First, it sets a renewable content minimum, 5% annual average renewable content in the gasoline fuel class, and 4% renewable content in the diesel fuel class. Second, it sets declining annual carbon intensity targets for each fuel class. In 2020, the regulation was amended to increase the stringency of the targets equating to an overall carbon intensity reduction of 20% to be achieved by 2030. The new annual carbon intensity reduction schedule is presented in Table 2.

Table 2

LCFS Carbon Intensity Reduction Schedule

Compliance Period	Percentage Reduction	Carbon Intensity Limit for Diesel Class Fuel (g CO_2e/MJ)	Carbon Intensity Limit for Gasoline Class Fuel (g CO_2e/MJ)
2020	-9.1%	86.15	80.13
2021	-10.2%	85.11	79.17
2022	-11.3%	84.08	78.20
2023	-12.4%	83.04	77.24
2024	-13.5%	82.01	76.28
2025	-14.5%	80.98	75.32
2026	-15.6%	79.94	74.36
2027	-16.7%	78.91	73.40
2028	-17.8%	77.88	72.44
2029	-18.9%	76.84	71.47
2030 and subsequent compliance periods	-20%	75.81	70.51

Note. Carbon intensity limits represent life cycle values. From B.C. LCFS Requirements. Retrieved from https://www2.gov.bc.ca /gov/content/ industry/electricity-alternative-energy/transportation-energies/renewable-low-carbon-fuels/fuel-supplier-compliance-50005

In order to comply with the LCFS, fuel suppliers must calculate their fuel carbon intensity for the compliance year for all fuels sold in the province. If the fuel supplier’s annual carbon intensity is below the limit, they can generate credits. If it is above the limit, they will receive debits. Credits can be sold to other fuel suppliers that require them.

The LCFS market in 2019 reported 263,512 credits exchanged with an average value of $206.23/credit totaling a $70,971,687 market (Low Carbon Fuel Credit Market Report - Quarterly, 2020). The LCFS creates a significant market pull for low carbon fuels which in turn, reduces GHG emissions. In 2018, the LCFS reduced 1.49 Mt of GHGs, and a total of 9.22 Mt between 2010 and 2018 (Renewable and Low Carbon Fuel Requirements Regulation Summary: 2010-2018, 2020).

Fuel suppliers must use the default carbon intensity stipulated in the regulation or calculate a unique carbon intensity for their fuel based on an LCA. An LCA considers the emissions associated with the full life cycle of the fuel from growing the feedstock, to fuel production and distribution to end use combustion in a vehicle. The LCFS requires the use of the software model *GHGenius* 4.03a to calculate fuel carbon intensities and stipulates LCA methodological requirements in regulation. To incent fuel suppliers to calculate unique fuel codes, the default carbon intensities are purposefully set high. The default carbon intensity for hydrogen under the LCFS is 96.82 g CO_2e/MJ HHV. The default carbon intensities of other fuels under the LCFS are presented in Table 3.

Table 3

LCFS Default Carbon Intensities

Fuel	Carbon Intensity ($g\ CO_2e/MJ$)
Renewable fuel in relation to diesel class fuel	98.96
Propane	75.35
Renewable fuel in relation to gasoline class fuel	88.14
Natural gas-based gasoline	90.07
Liquefied Natural Gas	112.65
Compressed Natural Gas	63.64
Electricity	19.73
Hydrogen	96.82

Note. Carbon intensity defaults represent life cycle values. From Renewable & Low Carbon Fuel Requirements Regulation. (2008). Retrieved from http://www.bclaws.ca/civix/document /id/ complete /statreg/394_2008

If a fuel supplier can provide evidence through an LCA (using *GHGenius* 4.03a), to support a lower carbon intensity fuel, they can submit a proposal to the Director of the LCFS Branch at the B.C. Ministry of Energy, Mines and Low Carbon Innovation and obtain a new fuel code. Fuel suppliers can then use that fuel code with the lower carbon intensity to obtain credits towards lowering their overall annual carbon intensity as required by the LCFS.

In addition to requiring renewable content minimums and setting annual carbon intensity reduction requirements, the LCFS spurs growth in the clean fuels industry through the Part 3 Agreement Program. Under this program, fuel suppliers can obtain credits for undertaking projects that increase the use of low carbon fuels sooner than would otherwise happen. The intent is to promote innovation while reducing GHG emissions resulting from the use of lower carbon fuels. Since 2019, 23 projects have been awarded over 800,000 credits and committed to investing over $450 million dollars in emissions reductions in the B.C. fuels industry ("Part 3 Agreements", n.d., para. 1).

Greenhouse Gas (Clean Energy) Reduction Regulation.

The *Clean Energy Act* sections 18 and 35(n), provides the authority allowing government to set out prescribed undertakings which utilities may choose to carry out to reduce GHG emissions, while recovering the cost in rates (Greenhouse Gas Reduction Regulation, n.d., para. 1). If a utility meets the requirements of the prescribed undertaking as set out in the Greenhouse Gas (Clean Energy) Reduction Regulation (GGRR), the utility is exempt from requiring a Certificate of Public Convenience and Necessity issued by the B.C. Utilities Commission (BCUC). However, the BCUC must rule on whether the project, program, contract, or expenditure satisfies the conditions of a prescribed undertaking. A prescribed undertaking is an enabling provision allowing utilities to acquire clean energy and recover costs incurred with respect to the prescribed undertaking in rates. An example of a prescribed undertaking is GGRR section 3.8, regarding a public utility's ability to acquire renewable natural gas (RNG). The regulation sets out a maximum price the utility can pay ($30/GJ), and the maximum volume of RNG allowed to be acquired under the prescribed undertaking (5% of the total volume of natural gas provided by the public utility to non-bypass customers in 2015). This policy enables low carbon fuel production by sending a strong market signal to producers, while limiting risk to rate payers by setting a volume cap.

European Union

CertifHy.

In June 2014, the European Fuel Cells and Hydrogen Joint Undertaking's (FCHJU) project CertifHy was established to develop a framework for the generation of Guarantees of Origin (GOs) for green and low carbon hydrogen. "A GO is per definition an instrument that labels the origin of a product and provides information to customers on the source of their products. It operates as a tracking system ensuring the quality of a product such as hydrogen or electricity" (CertifHy, 2019b, p.9). GOs are a mechanism that demonstrate compliance with the European Renewable Energy Directive recast to 2030 (RED II), which sets a renewable energy target of at least 32% by 2030 for Member States (European Union Science Hub, 2019). This is intended to reflect a 40% reduction in GHG emissions with respect to 1990 levels. RED II also sets a 14% renewable energy by 2030 target in transportation fuels, and a 1.3% yearly increase in the share of renewable energy in heating and cooling. Renewable fuels must comply with sustainability criteria set out in RED II to be counted towards the overall 14% target and to be eligible for financial support by public authorities (European Union Science Hub, 2019). Further to these targets, biofuel used in transportation must achieve a 60% reduction in emissions from the fossil fuels they replace.

The CertifHy GO scheme sets out criteria for hydrogen that must be fulfilled in order to be labelled "CertifHy green hydrogen" or "CertifHy low-carbon hydrogen" to demonstrate compliance with RED II. "CertifHy green hydrogen" is the proportion of hydrogen produced from renewable energy (e.g., wind, solar, hydro). "The greenhouse gas impact of electricity used for hydrogen production shall be considered to be equal to zero for electricity from wind, solar photovoltaic, and hydropower" (CertifHy, 2019a, p.8).

"CertifHy low-carbon hydrogen" is defined as hydrogen produced with a carbon intensity equal to or lower than 36.4 g CO_2e/MJ hydrogen LHV. Hydrogen produced from non-renewable feedstocks (e.g., natural gas), must meet or exceed this benchmark in order to receive CertifHy certification as "low carbon hydrogen". The benchmark represents a 60% reduction from a fossil fuel-derived hydrogen baseline of 91 g CO_2e/MJ. The baseline was determined on an LCA of large-scale, centralized hydrogen production via natural gas SMR using best achievable technology. The 60% reduction was selected based on regulatory requirements under RED II.

The LCA methodology used to calculate the CertifHy SMR carbon intensity baseline of 91 g CO2e/MJ has not been published. This creates uncertainty surrounding the methodological choices undertaken during the LCA in determining the baseline carbon intensity. In addition, the CertifHy working group could not reach consensus on the methodology for the carbon intensity of the SMR + CCS pathway, creating considerable uncertainty, and this deliverable remains an outstanding work packet.

> As previously indicated, no consensus was reached on the footprint calculation method for hydrogen from an SMR with CO_2 capture, due to differing views on how to handle carbon capture and utilisation (CCU). As this is a general question that extends beyond the scope of CertifHy, the discussion will need to be extended to a wider group of stakeholders, in order to address the various dimensions of the issue, considering common practice for life cycle analysis of CCU, international standards such as ISO 14067, provisions in the existing EU regulatory framework, and the point of view of the European policy makers (CertifHy, 2019b, p. 28).

In summary, a broad range of literature exists on the LCA of hydrogen production. However, due to the abundance of choice in methodological approach, it is difficult to compare results from one study to another. As the CertifHy process uncovered, having a clearly defined LCA methodology is missing and critical. “Certification of origin and sustainability metrices are key for political support, social acceptance, and consumer willingness to pay the premium for low-carbon and renewable hydrogen supply and applications” (Hydrogen Council, 2021, p. 22). This study proposes a low carbon intensity hydrogen benchmark and policy options to incent production. The results will contribute to the body of academic knowledge by providing LCA results specific to hydrogen production in B.C.

Methodology

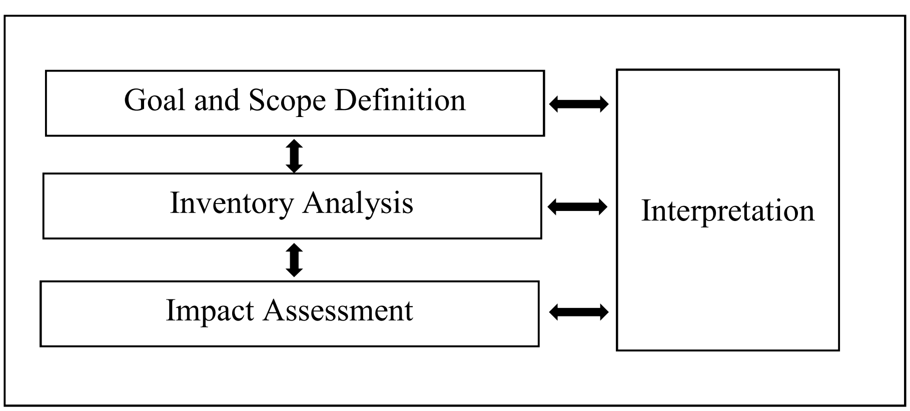
Goal and Scope Definition

The goal of this study is to compare the carbon intensities of three hydrogen production pathways in B.C. on a life cycle assessment (LCA) basis and identify the lowest carbon intensity pathway. The three selected hydrogen production pathways are steam methane reformation (SMR), SMR with carbon capture and storage (CCS), and electrolysis using B.C.’s low carbon gird electricity mix. These three methods were selected as they are commercially available and ready to deploy. SMR is the most common method of hydrogen production in the world (IEA, 2019), and is used in this study to provide the baseline carbon intensity for fossil fuel-derived hydrogen. The SMR + CCS and electrolysis pathways were chosen because they have unique feedstock and technical requirements that can be achieved in B.C. (B.C. Hydrogen Study, 2019). SMR + CCS captures and sequesters CO_2 deep underground in geological formations, yielding a low carbon hydrogen product (Hydrogen Council, 2021). B.C. has abundant natural gas reserves readily available to be used as feedstock for hydrogen production at scale (B.C. Hydrogen Study, 2019). These reserves are located in northeast B.C., nearby geological formations with suitable characteristics for CO_2 sequestration such as depleted gas pools and saline aquifers. In addition, establishing an SMR + CCS industry in B.C. would increase economic development while progressing Canadian CCS technologies and expertise, which can then be transferred around the world to other CCS projects coming online (CMC Research Institutes, 2021). The electrolysis using renewable electricity pathway was selected because it has the potential to produce a very low carbon hydrogen and B.C. currently has an abundance of hydroelectricity for use as a feedstock.

The LCA method was selected because it is an internationally recognized method that systematically considers all of the inputs that go in to making a product and assesses the environmental impact of the outputs (ISO, 2006). The emissions from fuels is often determined using the LCA method as it offers flexibility of the system boundary, considers the global warming impact of specific gases of interest, and is the required methodology under the B.C. Renewable and Low Carbon Fuel Requirements Regulation. An overview of the LCA framework is presented in Figure 1.

Figure 1

Life Cycle Assessment Framework



The system boundary selected for this study reflects a partial well-to-gate LCA. This system boundary includes all emissions from feedstock recovery and upgrading, feedstock transmission, and fuel production. The term 'gate' is intended to symbolize the plant gate whereby the finished fuel leaves the plant at the gate.

Functional unit.

The functional unit chosen for this study is 1 MJ of hydrogen, higher heating value (HHV) basis. This is consistent with case studies that use an energy functional unit as it refers to the energy content of the hydrogen (Valente et al., 2017). The results of the LCA are reported as grams of carbon dioxide equivalent per MJ (g CO_2e/MJ) hydrogen.

Allocation method.

When a process studied under LCA represents a multifunctional process (i.e., has more than one product), the emissions associated with the other processes or coproducts must be allocated between the outputs. ISO 14044 recommends system expansion wherever possible to avoid the need for allocation. If this is not possible then the options are allocation based on physical (i.e., mass or energy) or economic considerations (Brander, Tipper, Hutchison & Davis, 2009). *GHGenius* is an attributional LCA that uses mostly system expansion (or displacement) for co-products. For hydrogen production, *GHGenius* does not identify any co-products therefore allocation is avoided (D. O'Connor, personal communication, March 26, 2021). This excludes processes that use hydrogen production co-products when using the default settings in the model such as a CO_2 co-product used in enhanced oil recovery (EOR). The system boundary for the SMR + CCS pathway is not expanded to include EOR, and the LCA would not credit the emissions associated from CO_2 produced elsewhere. Since no co-products are identified for hydrogen production, the system boundary in the SMR + CCS pathway in this study represents permanent geological storage of the CO_2.

Impact Category and Life Cycle Impact Assessment Method

The impact category selected for this study is global warming potential (GWP). GWP is defined as the impact of human emissions on the radiative forcing (i.e., heat radiation absorption) of the atmosphere, which causes temperature rise at the earth's surface (Bhandari et al., 2012). In order to convert life cycle inventory data into an environmental impact such as GWP, the life cycle impact assessment method (LCIA), used was the IPCC method based on the IPCC's Fourth Assessment Report. The IPCC method characterises different gaseous emissions according to their GWP and is one of the most widely used methods in LCIA (Hischier & Weidema, 2010).

Other LCIA methods include Centre of Environmental Science of Leiden University (CML), Eco-indicator 99, Cumulative energy demand, and Ecological footprint. The IPCC method is specifically designed to assess impacts in the GWP impact category and therefore well adapted to meet the goal and scope of this study. It is also the default LCIA method included in the *GHGenius* 4.03a software model.

Data and Initial Data Quality Requirements

The LCA model software *GHGenius* 4.03a was used for this study. It contains a comprehensive LCA dataset with values specific to Canada, including B.C. as a regional option. It was developed for Natural Resources Canada by S&T^2 Consultants Inc. and is the required model for calculating fuel carbon intensity under the B.C. Renewable and Low Carbon Fuel Requirements Regulation. *GHGenius* is a spreadsheet-based program that allows users to adjust inputs and provides transparency by showing calculation formulas for each cell. Sources of data used by the program include Statistics Canada, industry reports, and engineering reports.

Spreadsheet type LCA models integrate the life cycle inventory, the impact assessment, and the results (D. O'Connor, personal communication, September 22, 2020). Limitations of this software include the dated nature of the original inputs, using industry average data, assumptions made (i.e., efficiency improvement percentages), and the overall length of time required by the user to learn how to use the model. There is high confidence in the data and assumptions used by this model given it contains values specific to the country and province of study, and its required use under regulation to determine the life cycle carbon intensity of fuels.

Methodological Assumptions

All three hydrogen production scenarios were modeled using *GHGenius* 4.03a. The region was set to B.C. with 2020 as the reference year of production. Carbon intensities were calculated for compressed hydrogen using the high heating value. Emissions included in the carbon intensity calculation were CO_2, methane (CH_4), and nitrous oxide (N_2O). The GWPs used were based on IPCC 2007 Fourth Assessment Report 100-year GWPs (CO_2 = 1, CH_4 = 25, and N_2O = 298). A summary of the key LCA methodological choices for this study is provided in Table 4.

Table 4

Key LCA Methodological Choices

Location	B.C.
Year	2020
Functional Unit	g CO_2e/MJ hydrogen
Emissions included in CO_2e	CO_2, CH_4, and N_2O
GWP	IPCC 2007 (1, 25, 298)
Atmospheric Lifetime	100 years
Heating Value of Fuels	High Heating Value (HHV)

Default *GHGenius* 4.03a values for energy content and density were used, as well as the assumption that all compression energy comes from electricity, and the purity of hydrogen produced from natural gas is 99.99% and 100% from electrolysis (S&T^2 Consultants Inc., 2013a). *GHGenius* 4.03a default values are summarized in Appendix A.

Assumptions pertaining to the system boundary such as emissions associated with vehicle materials, manufacture and transport were not included in the carbon intensity of the hydrogen, as the carbon intensity reflects emissions associated with the fuel and not the vehicle. Emissions associated with the construction of fuel production facilities were considered to be insignificant and treated as zero.

Emissions associated with direct land use change (LUC) include emissions from activities and processes associated with changing the use of land from one use to another e.g., feedstock exploration, production, recovery, and transportation including the construction of access roads and pipelines, and fuel production (B.C. Ministry of Energy, Mines and Petroleum Resources, 2018). The emissions associated with LUC from natural gas production were considered to be insignificant and treated as zero (D. O'Connor, personal communication, February 25, 2021). Emissions associated with LUC from B.C. grid electricity production includes significant methane emissions from decaying organic matter (e.g., trees) left behind in a hydroelectric dam. Effects related to indirect land use change are not included in the model.

The transmission of natural gas includes emissions related to moving the gas from the gas plant to the hydrogen production unit. The natural gas emission factors included all losses. There are very few feedstock transmission emissions allocated to electricity distribution, approximately 8%.

This study uses B.C. emission factors for natural gas and electricity. In the reference year 2020, the *GHGenius* 4.03a emission factor for natural gas was 58,896 g CO_2e/GJ (50,570 g CO_2e/GJ combustion and 8,201 g CO_2e/GJ production). In 2020, the model uses an electricity emission factor of 18,876 g/GJ or 67.95 g/kWh.

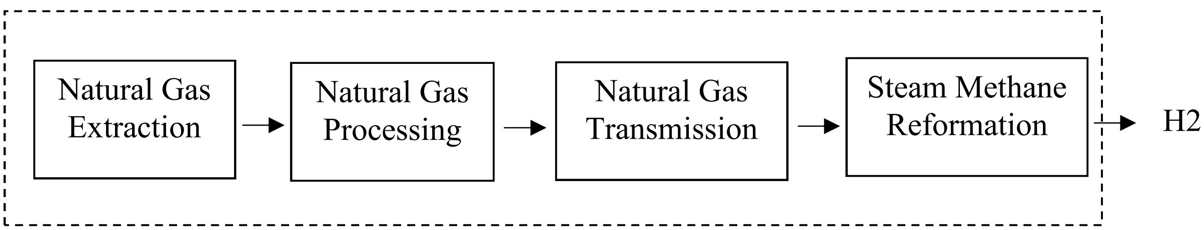
Inventory Analysis

Scenario 1: Steam methane reforming (SMR).

In scenario 1 (S1) natural gas feedstock from northeast B.C. is transported 100 km to an SMR hydrogen production unit. The system boundary of the LCA is shown in Figure 2.

Figure 2

System Boundary of SMR Pathway



The SMR information in *GHGenius* 4.03a is modelled on a small scale SMR unit designed for the average Canadian service station selling 5 million litres of gasoline per year (supplying about 2500 vehicles). This equates to approximately 2000 kg of hydrogen per day (S&T[2] Consultants Inc., 2013b, p. 339).

The energy inputs for the SMR unit in 2020 are 36,501.71 litres natural gas and 2.26 kWh of electricity per GJ of hydrogen produced. The model assumes a system efficiency of 68% in base year 1996 and an assumed efficiency improvement rate of 0.20% per year. The SMR energy inputs in 2020 are presented in Table 5.

Table 5

Energy Input Values for SMR in 2020

Hydrogen Production	Value	Units
Natural gas use in 2020	36,501.71	Litres CH_4/GJ H_2
Electricity use in 2020	2.26	kWh/GJ H_2

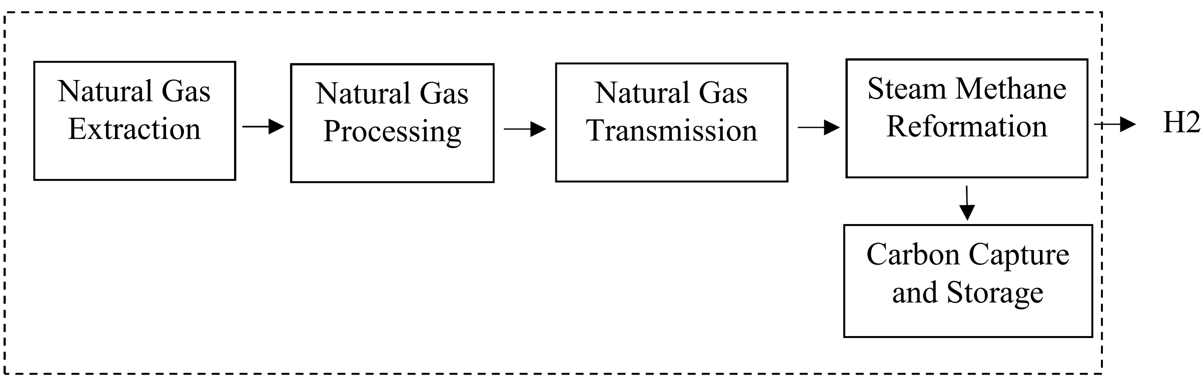
Note. Data obtained from LCA model *GHGenius* 4.03a.

Scenario 2: SMR + carbon capture and storage (CCS).

Scenario 2 (S2) includes the SMR production as described in S1 plus the addition of CCS. The system boundary for SMR + CCS is shown in Figure 3.

Figure 3

System Boundary for SMR + CCS Pathway



The *GHGenius* 4.03a model assumes an amine scrubber is used to separate CO_2 from the hydrogen and assumes a carbon capture efficiency of 85%. The default values in the model include the processes of carbon capture, transmission, and injection. There are additional energy inputs required for CCS and the model assumes 3.6 GJ/tonne for the extra energy required to capture, concentrate, and compress the CO_2 (S&T[2] Consultants Inc., 2013, p. 307). The fuel used in the pathway (natural gas) is modelled to supply the heat portion of the requirements (2.5 GJ/tonne of CO_2) with the remainder used for power. An additional 11.64 kWh of electricity and 2814.21 litres of natural gas per GJ of hydrogen produced is required to operate the CCS processes. The energy input values for the carbon capture process, separate from the fuel production requirements, are presented in Table 6.

Table 6

Energy Input Values for the Carbon Capture Process in 2020

Fuel	Hydrogen
Feedstock	Natural gas
Base Year	2005
Inputs per output	GJ
Fraction CO_2 sequestered	.85
Electricity (kWh)	12.00
Percent change per year	-0.20
Calculated in 2020	11.64
Natural gas (L)	2,900.00
Percent change per year	-0.20
Calculated value in 2020	2,814.21
kJ spent/GJ produced	148,437
g sequestered/GJ produced	42,660
GJ/Tonne CO_2 captured	3.480

Note. Data obtained from LCA model *GHGenius* 4.03a

The total energy input values for SMR + CCS in 2020 are 39,315.92 litres of natural gas and 13.90 kWh of electricity, per GJ of hydrogen. The model assumes an annual rate of improvement of 0.20% with 2005 as the base year. The total SMR + CCS energy inputs in 2020 are presented in Table 7.

Table 7

Energy Input Values for SMR + CCS in 2020

Hydrogen Production	Value	Units
Natural gas use in 2020	39,315.92	Litres CH_4/GJ H_2
Electricity use in 2020	13.90	kWh/GJ H_2

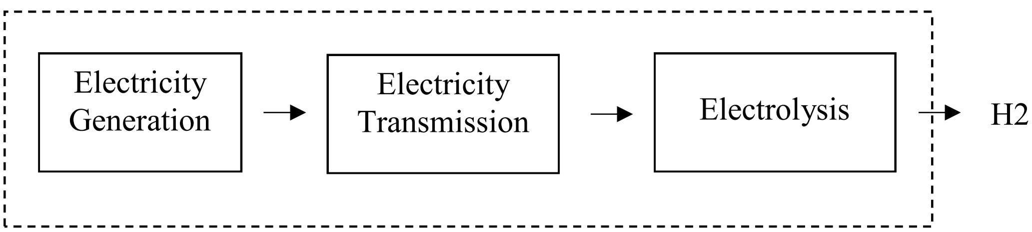
Note. Data obtained from LCA model *GHGenius* 4.03a.

Scenario 3: Electrolysis.

Scenario 3 (S3) includes using the B.C. low carbon grid electricity mix to produce hydrogen via electrolysis using an alkaline electrolyzer. The system boundary is shown in Figure 4.

Figure 4

System Boundary for Electrolysis Pathway



The *GHGenius* 4.03a default values for the B.C. grid electricity mix in the year 2020 are hydro (84%), biomass (9%), gas boiler (5%), and wind (3%). The default B.C. grid electricity mix values are presented in Table 8.

Table 8

B.C. Grid Electricity Mix Values in 2020

Source	British Columbia
Hydro	84%
Biomass	9%
Gas Boiler	5%
Wind	3%
Coal	0%
Nuclear	0%
Oil	0%

Note. Data obtained from LCA model *GHGenius* 4.03a.

The *GHGenius* 4.03a energy input value required in the year 2020 for electrolysis is 359.43 kWh/GJ hydrogen. This value is assumed to include any power conditioning and rectification that is required by the system ($S\&T^2$ Consultants Inc., 2013, p. 340). A summary of the hydrogen production energy inputs for all scenarios in 2020 is presented in Table 9.

Table 9

Summary of Energy Input Values by Pathway in 2020

Hydrogen Production	Value	Units
SMR		
Electricity use in 2020	2.26	kWh/GJ H_2
Natural gas use in 2020	36,501.71	Litres CH_4/GJ H_2
SMR + CCS		
Electricity use in 2020	13.90	kWh/GJ H_2
Natural gas use in 2020	39,315.92	Litres CH_4/GJ H_2
Electrolysis		
Electricity use in 2020	359.43	kWh/GJ H_2

Note. Data obtained from LCA model *GHGenius* 4.03a.

Results and Discussion

The resulting carbon intensities for scenarios 1, 2 and 3 are 82.75, 26.07, and 24.42 g CO_2e/MJ HHV respectively. Scenarios 2 and 3 provide significant GHG reductions when compared to the fossil fuel-derived baseline (S1). The carbon intensity from SMR + CCS (S2) results in a 68% carbon intensity reduction from S1, and hydrogen produced from electrolysis using the B.C. low carbon grid electricity mix (S3) results in a 70% reduction. The carbon intensity results from each stage of the life cycle and totals for each scenario are presented in Table 10.

Table 10

LCA Carbon Intensity Results (g CO_2e/GJ)

Scenario #	**1**	**2**	**3**
Source of Emissions	SMR	SMR+CCS	Electrolysis
Region	B.C.	B.C.	B.C.
Fuel (compressed)	Hydrogen	Hydrogen	Hydrogen
Feedstock	Natural Gas	Natural Gas	Electricity
Fuel Dispensing	1221	1221	1221
Fuel Distribution and Storage	10040	10040	10047
Fuel Production	70278	12645	24423
Feedstock Transmission	574	618	0
Feedstock Recovery	6969	7506	0
Feedstock Upgrading	0	0	0
Land-use Changes, Cultivation	0	0	0
Fertilizer Manufacture	0	0	0
Gas Leaks and Flares	3543	3816	0
CO_2, H_2S removed from NG	1381	1487	0
Emissions Displaced	0	0	0
Emissions from Fuel Use			
Total (g CO_2e/GJ)	94005	37333	35690
Total (g CO_2e/MJ)	94.01	37.33	35.67
Well-to-Gate Total (g CO_2e/MJ)	**82.75**	**26.07**	**24.42**

Note. Well-to-gate LCA, 100 km feedstock transport distance, reference year 2020. Data obtained from LCA model *GHGenius* 4.03a. LCA results do not reflect actual emissions.

In each scenario, the life cycle component with the most significant amount of emissions was fuel production with 70.23, 12.65 and 24.42 g CO_2e/MJ respectively. The fossil fuel-derived hydrogen results are in alignment with the literature and are expected due to the nature of removing carbon from the feedstock to isolate hydrogen. Spath and Mann (2001) noted 74.8% of emissions from SMR-derived hydrogen were attributable to the hydrogen production unit.

Scenario 1 (SMR)

The results of this study for S1 are 82.75 g CO_2e/MJ hydrogen HHV (11.7 kg CO_2e/kg). This in agreement with the literature reviewed as presented in Table 11.

Table 11

Summary of Carbon Intensities from SMR-derived Hydrogen

Reference	Carbon Intensity	Conversion to Comparable Units (kg CO_2e/kg H_2)	Comments
Antonini et al. (2020)	90 g CO_2e/MJ	10.8	LHV
Bhandari et al. (2012)	8.9 – 12.9 kg CO_2e/kg	8.9 – 12.9	
CertifHy (2019a)	91 g CO_2e/MJ	10.9	LHV
IEA (2019)	8.5 kg CO_2e/kg	8.5	Fuel transmission and distribution not included
Layzell et al. (2020)	10.72 kg CO_2e/kg	10.72	
Ramsden et al. (2013)	110.3 g CO_2e/MJ	13.23	LHV, fuel compression, storage and dispensing not included
Spath & Mann (2001)	11,888 g CO_2e/kg	11.9	

Comparing the carbon intensity results is challenging due to many factors. Most noticeably, the functional unit chosen in each study is not the same. This requires recalculating the results to common units to make comparisons easier. In many of the LCA's reviewed, there was little information provided on the scope of the study or system boundary, making it difficult to know what stages in the life cycle were included in the carbon intensity calculation (e.g., fuel distribution and storage). Other key pieces of information that were not disclosed included feedstock transmission distances, identification of coproducts and allocation method, and whether the results were reported on a low or high heating value. This information could have a significant impact on emissions and without a clear description of each pathway, interpretating the results and drawing conclusions proved difficult. Since each LCA represents a unique scenario, presenting a range of carbon intensities per pathway appears to be a more appropriate way to indicate the variability of the LCA method. Bhandari et al. (2012) summarized GWP values from several hydrogen LCA studies and reported a range for SMR between 8.9 to 12.9 kg CO_2e/kg hydrogen.

Scenario 2 (SMR + CCS)

With SMR + CCS, the discussion points above apply, plus the addition of assumptions pertaining to CCS, mainly the percent carbon capture and source of power for CCS. Layzell et al. (2020) noted SMR + CCS (with 90% capture), resulted in production emissions of 0.97 kg CO_2e/kg, plus upstream (natural gas recovery) and infrastructure emissions of 1.84 kg CO_2e/kg, resulting in total emissions of 2.8 kg CO_2e/kg. The S2 results of this study are 26.07 g CO_2e/MJ (or 3.7 kg CO_2e/kg) hydrogen HHV basis. These results are slightly higher than the findings of Layzell et al. (2020) possibly due to this study only modelling an 85% capture rate, however without details of the methodology undertaken by Layzell et al., it is impossible to know exactly why the results differ. The S2 results of this study, 26.07 g CO_2e/MJ HHV (3.7 kg CO_2e/kg), are in alignment with the literature reviewed as presented in Table 12.

Table 12

Summary of Carbon Intensities from SMR + CCS-derived Hydrogen

Reference	% Carbon Capture	Carbon Intensity (kg CO_2e/kg H_2)	Comments
Antonini et al. (2020)	-	2.64 - 5.76	22-48 gCO_2e/MJ LHV
CertifHy (2019a)	-	4.37	36.4 g CO_2e/MJ LHV, 60% reduction from SMR baseline
IEA (2019)	56%	4	Fuel transmission and distribution not included
IEA (2019)	90%	2	Fuel transmission and distribution not included
Layzell et al. (2020)	90%	2.8	

Scenario 3 (Electrolysis)

Of the three hydrogen production scenarios modelled, hydrogen produced from electrolysis using the B.C. low carbon grid electricity mix resulted in the lowest carbon intensity. This is due to the significant portion of hydroelectricity (84%) of the B.C. grid electricity mix input value used in *GHGenius* 4.03a for reference year 2020. As cited by Valente et al. (2017), the source of energy and raw materials are key aspects determining the life cycle performance, and this is particularly relevant for electrolysis pathways as emissions are strongly dependant on the energy source.

Most electrolytic LCAs using renewables focus on wind with a significant portion (78%) of emissions attributed to turbine production and operation (Spath & Mann, 2004). Other LCA studies using the grid electricity mix for a given region resulted in a wide range of carbon intensities due to the varied sources of the electricity. Dufour et al., 2012 (as cited in Bhandari,

2012) presented a carbon intensity of 2.6 kg CO_2e/Nm^3 hydrogen based on the European grid mix (34% nuclear, 33% coal, 19% natural gas and oil, 9% hydro, and 5% renewable). Wulf and Kaltschmitt (2012) (as cited in Bhandari, 2012) analyzed hydrogen LCA results from the German grid electricity mix (the majority fossil, 22% nuclear, and 6% renewable), which resulted in a carbon intensity of 32 kg CO_2e/kg hydrogen. In this study, the result of S3 was 24.42 g CO_2e/MJ hydrogen (or 3.45 kg CO_2e/kg). This demonstrates the wide range of carbon intensities when using the grid electricity mix as it depends on the sources of generation in the mix. A summary of carbon intensities from electrolytic hydrogen production using renewable electricity is presented in Table 13.

Table 13

Summary of Carbon Intensities from Electrolytic Hydrogen

Reference	**Electricity Source**	**Carbon Intensity** (kg CO_2e/kg H_2)	**Comments**
Bhandari et al. (2012)	Green	4.1	
Bhandari et al. (2012)	Wind	2.4	20 gCO_2e/MJ
IEA (2019)	Renewable	0.0	Fuel transmission and distribution not included
Layzell et al. (2020)	Large hydro	1.0	
Spath & Mann (2004)	Wind	0.97	Cradle-to-Grave

The S3 result of this study is in alignment with the literature, given the broad range of carbon intensity values for hydrogen produced via electrolysis using renewable energy or grid mix electricity. The conclusion that the S3 pathway produces the lowest carbon intensity hydrogen is consistent with Ozbilen (as cited in Bhandari, 2012) that notes renewable energy-based electrolysis has a much lower effect on the environment when compared to SMR.

Uncertainties

Selecting the location in the model has a significant impact on the LCA results as once selected, the model automatically defaults to input values specific to that region. For electrolysis pathways, regions with a greater percentage of fossil fuel-derived grid electricity (e.g., Canadian average, Alberta), would be expected to result in hydrogen with a higher carbon intensity. Location selection also affects the carbon intensity of natural gas pathways as the input values are tailored to the specified region.

Another key factor in determining the carbon intensity of a fuel is whether or not the LCA model used includes land use change (LUC) emissions. An example of this is the *GHGenius* 4.03a model includes LUC emissions resulting in a 2020 B.C. electricity grid emission factor of 18.88 g/MJ. Another emission quantification methodology required to be used by B.C. Public Sector Organizations (i.e., universities and hospitals), to calculate their GHG emissions, does not include LUC resulting in an B.C. electricity grid emission factor of 8.3 g/MJ. In addition, the latter also includes emissions from electricity imports and exports, whereas the *GHGenius* value does not. These methodological variances affect carbon intensity and make comparisons of results difficult (Valente et al. 2017).

Correctness of the default data values in the LCA dataset is also an important consideration in calculating accurate results. For example, if emissions from natural gas production and transmission are underestimated (e.g., due to the difficulty in measuring methane leaks), the LCA carbon intensity results for S1 and S2 would be lower than actual, given natural gas is the feedstock. In addition, in the S2 pathway, the percent carbon capture used in the model will have a direct impact on carbon intensity results. Lastly, the selected allocation method has the potential to significantly impact results depending on the product being assessed and any co-products identified. In summary, the results of this study generally align with the literature. However, due to variability in LCA methodology, assumptions, and the uniqueness of each LCA scenario, it is challenging to make comparisons and draw accurate conclusions.

Barriers to Increasing Low Carbon Intensity Hydrogen Production in B.C.

Barriers to increasing low carbon hydrogen production in B.C. include matching supply to demand, infrastructure build out and compatibility, ensuring enabling policies and safety regulations are in place, a general lack of public awareness about the benefits of hydrogen and the most significant barrier, economics.

The high cost of the S3 pathway presents a challenge to building out the hydrogen sector at scale. Hydrogen production via electrolysis using the B.C. grid electricity mix is expected to be $5-7/kg hydrogen based on an industrial electricity rate of $60/MWh (Megawatt-hour), this is representative of current industrial rate tariffs (B.C. Hydrogen Study, 2019, p. 41). Ivy (as cited in Bhandari, 2012) noted the cost of electrolytic hydrogen is largely dependent on the cost of electricity, the efficiency of systems and the capital costs of the systems. In comparison, SMR production is estimated at $1.32/kg hydrogen, and SMR + CCS is estimated at $2.14/kg hydrogen (B.C. Hydrogen Study, 2019, p. 44). In time, the cost of the electrolysis pathway is expected to decline due to improvements in electrolyzer efficiency and declining costs of the renewable electricity feedstock. “BloombergNEF predicts the global levelized cost of hydrogen from large renewable energy powered projects will be cost competitive with low carbon hydrogen from natural gas via SMR w/CCUS by 2030 and that by 2050, renewable hydrogen could be produced for less than a dollar per kilogram” (NRCan, 2020, p.34).

Economic Opportunities and Business Implications

As countries look to reduce emissions there is growing interest in hydrogen as a low or zero-carbon energy carrier. Global demand for hydrogen from B.C.'s near-by trading partners (e.g., China, Japan, South Korea, and California), is estimated to increase to 100 Mt by 2050 which represents a $15 billion-dollar annual opportunity if B.C. supplies 5% of this demand (B.C. Hydrogen Study, 2019). Scaling up production to meet demand presents an economic challenge. In order to be competitive with incumbent fossil fuels, Layzell et al. (2020) estimate the retail price target for hydrogen should be $3.50 to $5.00/kg when used in transportation applications, and $1.00 to $2.80 /kg in thermochemical applications.

Solutions to reduce costs include starting to build out the sector by establishing domestic hubs or nodes whereby hydrogen production is matched with off take (BloombergNEF, 2020, NRCan, 2020). This approach allows for logistics regarding production, transportation, and storage to be tested and solved, as well as provides time for increased provincial research and development. Demonstrations and piloting of innovative technologies will bring efficiency gains and result in technological advancement and commercialization. As production increases and costs decline, B.C. will benefit from domestic hydrogen production expertise and then can gradually transition to large-scale low carbon hydrogen production for the export market.

B.C. has many natural resource advantages making exporting hydrogen to global markets a viable possibility. Currently there is an excess of hydroelectricity for the production of green hydrogen via electrolysis, and an abundant volume of natural gas conveniently located near-by suitable geological formations for carbon capture and storage for the production of blue hydrogen (B.C. Hydrogen Study, 2019). As well, B.C. has the advantage of geographic proximity to export markets.

B.C. already has foundational policies in place such as carbon pricing and the LCFS, however more are required to attract investment. Government support will be instrumental in the initial build out of a hydrogen sector. For example, green bonds, loan guarantees, and tax incentives such as Section 45Q of the U.S. Internal Revenue Code. Section 45Q provides a performance-based tax credit of up to $50 per tonne for CCS, and up to $35 per tonne for EOR projects or other beneficial uses i.e., direct air capture (Congressional Research Service, 2018).

With an ever-increasing number of investors turning toward sustainable finance (Deloitte, 2020), there is also a growing opportunity to invest in clean energy projects. Sustainable finance invests in projects that incorporate environmental, social and governance (ESG) factors and result in sustainable growth. In addition, companies that meet ESG targets can benefit from reduced borrowing rates. This recent uptick in sustainable finance can open doors for the large-scale investment required to kick start the hydrogen economy.

As low carbon hydrogen scale-up is not here yet, investors are advised to watch for seven key events to help determine whether a hydrogen economy is emerging "1) legislated net-zero targets, 2) harmonized standards and regulatory barriers removed, 3) targets with investment mechanisms are introduced, 4) stringent heavy transport emission standards, 5) mandates and markets for low-emission products are formed, 6) industrial decarbonization policies and incentives are put in place and 7) hydrogen-ready equipment becomes commonplace" (BloomberNEF, 2020, p.9). Jurisdictions that are successful in attaining the investment to grow the hydrogen economy can also benefit from follow-on economic benefits such as the creation of high paying jobs. As investors wait for market assurance, government policies and subsidies will be critical to de-risk and aid the investment decisions of first movers.

Recommendations

Due to the current high cost of hydrogen produced via electrolysis using the B.C. grid electricity mix, fossil fuel-derived hydrogen with carbon capture (e.g., SMR + CCS) is a recommended bridging pathway in order for B.C. to realize the climate and economic benefits of a hydrogen economy. This would increase the supply of low carbon hydrogen, which in turn will increase demand, while utilizing existing oil and gas infrastructure. Leveraging the SMR + CCS pathway can bridge the gap until electrolysis with renewable electricity becomes more economical. However, even though less expensive than electrolysis, SMR + CCS also presents financial challenges as these projects are typically large scale and require significant investment. To incent the production of low carbon hydrogen and the transition to a low carbon economy, government support will be required through policy and funding.

To ensure emissions are kept to a minimum, government policies and funding should be targeted to only support hydrogen production from renewable sources or hydrogen derived from fossil fuels that can meet a carbon intensity benchmark. The benchmark should be reduced overtime to send a strong signal to industry of the priority for low carbon hydrogen and government's commitment to reducing emissions.

Establishing a Low Carbon Intensity Hydrogen Benchmark

There are many economic, environmental, and social factors to consider when establishing a low carbon benchmark for hydrogen including: competitiveness (e.g., aligning policies with other jurisdictions to incent production, increase domestic economic development and attract investment); technical feasibility of the benchmark; commercial availability of the technology; and whether the benchmark will achieve its purpose (e.g., reducing GHG emissions).

In establishing a low carbon intensity benchmark for this study, the principles of the EU's CertifHy GO scheme were applied. The EU's CertifHy GO scheme sets a low carbon hydrogen benchmark of 36.4 g CO_2e/MJ LHV (see p. 28). This benchmark represents a 60% reduction from an SMR hydrogen baseline carbon intensity of 91 g CO_2e/MJ LHV, determined on a life cycle basis. The 60% reduction policy is a requirement under RED II which states biofuels used in transportation must achieve a 60% reduction in emissions from the fossil fuels they replace.

Applying the same 60% reduction approach to the SMR baseline calculated in S1 (82.75 g CO_2e/MJ HHV or 97.36 g CO_2e/MJ LHV), results in a proposed benchmark of 33.10 g CO_2e/MJ HHV or 38.94 g CO_2e/MJ LHV. A 60% reduction from the S1 baseline is presented in Table 14.

Table 14

Scenario 1 Baseline SMR Carbon Intensity and 60% reduction

Life Cycle Stage	S1 HHV	S1 LHV
Fuel production	70,278	82,690
Feedstock transmission	574	675
Feedstock recovery	6,969	8,200
Gas leaks and flares	3,543	4,168
CO_2, H_2S removed from NG	1,381	1,625
Total (g CO_2e/GJ)	82,744	97,358
Total (g CO_2e/MJ)	**82.75**	**97.36**
60% reduction from Total	**33.10**	**38.94**

Sensitivity Analysis.

In order to attain a carbon intensity benchmark of 33.10 g CO_2e/MJ HHV / 38.94 g CO2e/MJ LHV, a sensitivity analysis was conducted on the percent carbon capture that would be required for S2 (SMR + CCS), to meet the benchmark. The percent carbon capture was increased and decreased to determine the effect on emissions. SMR with 50, 60, 70, 75, 80, 85, 90, 95 and 98% carbon capture were modelled as scenarios 2a, 2b, 2c, 2d, 2e, 2f, 2g, 2h and 2i respectively. The results of the sensitivity analysis are presented in Table 15.

Table 15

Carbon Intensity of SMR + CCS with 50 – 98% Carbon Capture Rates

Scenario # % Carbon Capture	**2a** 50%	**2b** 60%	**2c** 70%	**2d** 75%	**2e** 80%	**2f** 85%	**2g** 90%	**2h** 95%	**2i** 98%
Fuel production	38,928	31,419	23,909	20,155	16,400	12,645	8,890	5,136	2,883
Feedstock transmission	618	618	618	618	618	618	618	618	618
Feedstock recovery	7,506	7,506	7,506	7,506	7,506	7,506	7,506	7,506	7,506
Gas leaks and flares	3,816	3,816	3,816	3,816	3,816	3,816	3,816	3,816	3,816
CO_2, H_2S removed from NG	1,487	1,487	1,487	1,487	1,487	1,487	1,487	1,487	1,487
Total Well-to-Gate (g CO_2e/GJ)	52,356	44,846	37,337	33,582	29,827	26,073	22,318	18,563	16,310
Total Well-to-Gate (g CO_2e/MJ) HHV	**52.36**	**44.85**	**37.34**	**33.58**	**29.83**	**26.07**	**22.32**	**18.56**	**16.31**
Fuel production	45,804	36,968	28,132	23,714	19,296	14,878	10,461	6,043	3,392
Feedstock transmission	727	727	727	727	727	727	727	727	727
Feedstock recovery	8,832	8,832	8,832	8,832	8,832	8,832	8,832	8,832	8,832
Gas leaks and flares	4,490	4,490	4,490	4,490	4,490	4,490	4,490	4,490	4,490
CO_2, H_2S removed from NG	1,750	1,750	1,750	1,750	1,750	1,750	1,750	1,750	1,750
Total Well-to-Gate (g CO_2e/GJ)	61,602	52,767	43,931	39,513	35,095	30,677	26,259	21,842	19,191
Total Well-to-Gate (g CO_2e/MJ) LHV	**61.60**	**52.77**	**43.93**	**39.51**	**35.10**	**30.68**	**26.26**	**21.84**	**19.19**

Note. Shading indicates % carbon capture rate resulting in achieving a 60% emission reduction from SMR baseline (S1).

The results of the sensitivity analysis indicate to meet a carbon intensity benchmark of 33.10 g CO_2e/MJ HHV (38.94 g CO_2e/MJ LHV), an 80% carbon capture rate is required. This results in a carbon intensity of 29.83 g CO_2e/MJ HHV (35.10 g CO_2e/MJ LHV). This proposed benchmark can be achieved with current technology that is commercially available.

Although this benchmark does not eliminate emissions, it provides a 60% reduction from the fossil fuel baseline. It is intended to kick-start the hydrogen economy while signalling the necessity for low carbon hydrogen. It creates certainty for industry, allowing for longer-term planning, investment decisions, and diversification of the fossil fuel sector. In addition, the benchmark aligns with other jurisdictions for fossil fuel-derived hydrogen and allows an increase of less than 10 g CO_2e/MJ compared to the carbon intensity achieved with electrolysis using renewables as modelled in this study using a life cycle approach. In order to further reduce emissions from fossil fuel-derived hydrogen, a key part of the recommendation is for continued reductions in the carbon intensity benchmark over time. This provides a pathway to reducing emissions and the transition to a low carbon economy.

Policy Options to Incent Low Carbon Hydrogen Production in B.C.

The Greenhouse Gas (Clean Energy) Reduction Regulation (GGRR), is one option to enable low carbon hydrogen production in B.C. This could be achieved by amending the GGRR to include hydrogen as a prescribed undertaking (see p. 27). In order to be considered a prescribed undertaking, only hydrogen derived from renewable sources or fossil fuel-derived hydrogen that is able to meet a carbon intensity benchmark would be eligible e.g., 33.10 g CO_2e/MJ HHV (38.94 g CO_2e/MJ LHV), based on an LCA approach using *GHGenius*, with methodology stipulated in regulation.

To transition to hydrogen economy, long-term objectives could also be set by implementing a low carbon fuel mandate for hydrogen. One policy instrument that could be amended for this purpose is the Low Carbon Fuel Standard (LCFS), as it contains similar requirements for renewable content in the gasoline and diesel fuel pools (see p. 22). Additionally, the LCFS could be amended to include a new hydrogen fuel class, similar to gasoline and diesel, with a baseline carbon intensity. As with the other fuel classes, hydrogen would be subject to regulated annual reductions in carbon intensity in order to continuously reduce emissions.

If fuel suppliers cannot meet the requirement, even with credit trading allowances, then administrative penalties could be applied. This approach would require careful monitoring of the current volumes of hydrogen sold in the province and extensive consultation with industry in order to determine the appropriate time horizons and level to set the low carbon fuel mandate or baseline carbon intensity and annual reduction percentage.

Conclusion

A comparative well-to-gate LCA was performed using the *GHGenius* 4.03a model to determine the carbon intensities of three hydrogen production pathways in B.C. The carbon intensity results for scenario 1 (SMR), scenario 2 (SMR + CCS) and scenario 3 (electrolysis) were 82.75, 26.07, and 24.42 g CO_2e/MJ HHV, respectively. Of the three hydrogen production scenarios modelled, hydrogen produced by electrolysis using the B.C. grid electricity mix (S3) resulted in the lowest carbon intensity. This is due to the significant portion of hydroelectricity (84%) of the B.C. grid electricity mix in the modelled reference year 2020.

To maximize environmental benefits, low carbon hydrogen production from renewable sources via electrolysis is the recommended priority pathway for government policy support and funding. However, due to the current high cost of electrolytic hydrogen, approximately three to five times higher than fossil fuel-derived hydrogen with CCS, the latter is a recommended bridging pathway in order for B.C. to commence hydrogen production at scale and realize the environmental and economic benefits of a hydrogen economy.

To incent low carbon hydrogen production, only hydrogen derived from renewable sources or from fossil fuels with the ability to meet a carbon intensity benchmark (e.g., SMR + CCS) are recommended to be eligible for government subsidies. A carbon intensity benchmark of 33.10 g CO_2e/MJ HHV (38.94 g CO_2e/MJ LHV) (based on a 60% reduction from the SMR baseline calculated in S1) is proposed, in alignment with the EU's CertifHy GO scheme. Results of a sensitivity analysis indicate this benchmark can be achieved with an 80% carbon capture rate. Setting a carbon intensity benchmark for fossil fuel-derived hydrogen sends a strong signal to industry of the priority for low carbon hydrogen and the government's commitment to reducing emissions. Furthermore, reducing the carbon intensity benchmark over time, signals the long-term objective to transition to low carbon energy systems.

Key limitations of this study are that it represents three B.C. specific hydrogen production scenarios, and that it is difficult to compare results with other LCA studies due to the variability of inputs. General limitations of the LCA methodology include the abundance of choices available (e.g., functional unit, system boundary, reference region and impact assessment method), as these choices strongly affect the results and make comparisons to other studies difficult (Bhandari et al., 2012, Valente et al., 2017). This limitation becomes apparent when attempting to define a carbon intensity benchmark for low carbon hydrogen, as there is no consensus on methodological approach.

Suggestions for future research include collaboration with other jurisdictions to align LCA methodological approaches in defining a low carbon hydrogen benchmark. With future collaboration and methodological alignment, jurisdictions will benefit from clear policy direction and a level regulatory playing field. Another area of future research includes undertaking an economic impact analysis to better understand the business implications of a low carbon hydrogen economy in B.C. This would identify the risks and benefits to investors and may attract investment, leveraging B.C.'s geographic and natural resource advantages for growing the hydrogen sector.

Hydrogen can play a key role in decarbonizing hard-to-abate sectors and the transition to a low carbon economy. This transition will provide economic development opportunities, diversify the fossil fuel sector, support innovative technologies, and reduce emissions as we strive to fight climate change.

References

Antonini, C., Treyer, K., Streb, A., Van der Spek, M., Bauer, C., & Mazzotti, M. (2020). Hydrogen production from natural gas and biomethane with carbon capture and storage – A techno-environmental analysis. *Sustainable Energy Fuels*, *4*, 2967-2986. https://doi: 10.1039/d0se00222d

B.C. Hydrogen Study. (2019). Retrieved from https://www2.gov.bc.ca/assets/gov/government /ministries-organizations/zen-bcbn-hydrogen-study-final-v6.pdf

B.C. Ministry of Energy, Mines and Petroleum Resources. (2018). Carbon Intensity Records (Information Bulletin RLCF-006). Retrieved from https://www2.gov.bc.ca/assets/gov/ farming-natural-resources-and-industry/electricity-alternative energy/transportation/ renewable-low-carbon-fuels/rlcf006_-_carbon_intensity_records.pdf

B.C. Ministry of Energy, Mines and Petroleum Resources. (2019). B.C. Low Carbon Fuel Standard Avoided Emissions Policy: Intentions Paper for Consultation. Retrieved from https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/bc_low_carbon_fuel_ standard_avoided_emission_policy_-_intentions_paper_for_consultation.pdf

B.C. LCFS Requirements. (n.d.). Retrieved from https://www2.gov.bc.ca/gov/content/industry/ electricity-alternative-energy/ transportation-energies/renewable-low-carbon-fuels/fuel-supplier-compliance-50005

Bhandari, R., Trudewind, C. A., & Zapp, P. (2012). Life cycle assessment of hydrogen production methods - a review. Retrieved from http://www.fzjuelich.de/SharedDocs/ Downloads/IEK/IEK-STE/DE/Publikationen/research_reports/2012/report_06_2012.pdf?

Bhandari, R., Trudewind, C. A., & Zapp, P. (2013). Life cycle assessment of hydrogen production via electrolysis – A review. *Journal of Cleaner Production*, *85*, 151-163. https://doi.org/10.1016/j.jclepro.2013.07.048

BloombergNEF. 2020. Hydrogen Economy Outlook. Retrieved from https://data.bloomberglp .com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

Brander, Tipper, Hutchison, & Davis. (2009). Consequential and Attributional Approaches to LCA: A Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels. Ecometrica. Technical Paper TP090403A. 44. Retrieved from https://www. researchgate.net/publication/237335622_Consequential_and_Attributional_Approaches_to_LCA_A_Guide_to_Policy_Makers_with_Specific_Reference_to_Greenhouse_Gas_LCA_of_Biofuels

CertifHy. (2019a). CertifHy-SD Hydrogen Criteria. Retrieved from CertifHy website: https://www.certifhy.eu/images/media/files/CertifHy_2_deliverables/CertifHy_H2-criteria-definition_V1-1_2019-03-13_clean_endorsed.pdf

CertifHy. (2019b). Taking CertifHy to the next level – Roadmap for building a dual hydrogen certification infrastructure for Guarantees of Origin and for Certification of renewable hydrogen in transport. Retrieved from CertifHy website: https://www.certifhy.eu/images/media/files/CertifHy_2_deliverables/190319_CertifHy2_Roadmap_Final_Draft_as_endorsed_by_the_Steering_Group.pdf

CMC Research Institutes. (2021). *Exporting CCUS technology. An international business development strategy for Canadian carbon capture, utilization, and storage companies.*

Retrieved from https://cmcghg.com/wp-content/uploads/2021/03/CMC-Research-Report_FINAL.pdf

Congressional Research Service. (2018). *Carbon capture and storage in the United States.* Retrieved from http://large.stanford.edu/courses/2020/ph240/villanueva1/docs/R44902.pdf

Deloitte. (2020). Advancing environmental, social, and governance investing. A holistic approach for investment management firms. Retrieved from https://www2.deloitte.com/us/en/insights/industry/financial-services/esg-investing-performance.html

Environment and Climate Change Canada. (2017). Canadian Environmental Sustainability Indicators: Greenhouse Gas Emissions. Retrieved from www.ec.gc.ca/indicateurs-indicators/default.asp?lang=En&n=FBF8455E-1.

European Union Science Hub. 2019. Retrieved from https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii

Greenhouse Gas Reduction Regulation. (n.d.). Retrieved from https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/clean-transportation-policies-programs/greenhouse-gas-reduction-regulation

Hischier, R. & Weidema, B. 2010. Implementation of life cycle impact assessment methods. Retrieved from https://www.ecoinvent.org/files/201007_hischier_weidema_implementation_of_lcia_met hods.pdf

Hydrogen Council. (2021). Hydrogen decarbonization pathways: A life-cycle assessment. Retrieved from https://hydrogencouncil.com/wp-content/uploads/2021/04/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf

International Energy Agency [IEA]. (2019). The future of hydrogen: Seizing today's opportunities. Retrieved from https://www.iea.org/reports/the-future-of-hydrogen

International Energy Agency [IEA]. (2020). Tracking Transport 2020. Retrieved from https://www.iea.org/reports/tracking-transport-2020

International Standard Organization [ISO]. (2006). *Environmental management – Life cycle assessment – Principles and framework.* (Reference number ISO 14040:2006E).

International Panel on Climate Change [IPCC]. 2018. Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Retrieved from https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf

Layzell, D., Young, C., Lof, J., Leary, J., & Sit, S. 2020. Towards Net-Zero Energy Systems in Canada: A Key Role for Hydrogen. Transition Accelerator Reports: Vol 2, Issue 3. Retrieved from https://transitionaccelerator.ca/towards-net-zero-energy-systems-in-canada-a-key-role-for-hydrogen

Low Carbon Fuel Credit Market Report - Quarterly, (2020). Retrieved from https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/rlcf-017.pdf

Lozanovski, A., Schuller, O., & Faltenbacher, M. (2011). FC-Hy Guide: Guidance document for performing LCAs on fuel cells and H2 technologies. Brussels: FCH JU.

Muresan, M., Cormos, C. C., & Agachi, P. S. (2014). Comparative life cycle analysis for gasification-based hydrogen production systems. *Journal of Renewable and Sustainable Energy*, *6*(1), 013131. Retrieved from https://doi.org/10.1063/1.4864658

Natural Resources Canada [NRCan]. (2020). Hydrogen Strategy for Canada, Seizing the Opportunities for Hydrogen, A call to Action. Retrieved from https://www.nrcan.gc.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen%20Strategy%20for%20Canada%20Dec%2015%202200%20clean_low_accessible.pdf

Nie, Y., & Bi, X. (2018). Life-cycle assessment of transportation biofuels from hydrothermal liquefaction of forest residues in British Columbia. *Biotechnology for Biofuels*, *11*, 23. Retrieved from https://doi.org/10.1186/s13068-018-1019-x

Part 3 Agreements. (n.d.). Retrieved from https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/renewable-low-carbon-fuels/part-3-agreements

Provincial Inventory. (2015). Retrieved from https://www2.gov.bc.ca/gov/content/environment/climate-change/data

Ramsden, T., Ruth, M., Diakov, V., Laffen, M., & Timbario, T. A. (2013). Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios. Retrieved from https://www.nrel.gov/docs/fy14osti/60528.pdf

Renewable & Low Carbon Fuel Requirements Regulation. (2008). Retrieved from http://www.bclaws.ca/civix/document/id/complete/statreg/394_2008

Renewable and Low Carbon Fuel Requirements Regulation Summary: 2010-2018. (2020). Retrieved from https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/rlcf007_-_2018_summary_2010-18.pdf

S&T2 Consultants Inc. (2013a). GHGenius Model 4.03 Volume 1 Model Background and Structure. Natural Resources Canada

S&T2 Consultants Inc. (2013b). GHGenius Model 4.03 Volume 2 Data and Sources. Natural Resources Canada

S&T2 Consultants Inc. (2015). GHG Emission Reductions From World Biofuel Production and Use. Retrieved from www.ghgenius.ca

Scholz, R., & Tietje, O. (2002). Embedded case study methods. Retrieved from https://doi.org/10.4135/9781412984027

Simons, A., & Bauer, C. (2011). Life cycle assessment of hydrogen production. In A. Wokaun & E. Wilhelm (Eds.), Transition to Hydrogen: Pathways Toward Clean Transportation (pp. 13-57). Cambridge: Cambridge University Press. Retrieved from https://doi.org/10.1017/CBO9781139018036.006

Spath, P. L., & Mann, M. K. (2001). Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming. Retrieved from https://doi.org/10.2172/764485

Spath, P. L., & Mann, M. K. (2004). *Life Cycle Assessment of Renewable Hydrogen Production via Wind/Electrolysis: Milestone Completion Report*. United States.

United States Environmental Protection Agency. (2021). Global greenhouse gas emission data. Retrieved from https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

Valente, A., Iribarren, D. & Dufour, J. (2017). Life cycle assessment of hydrogen energy systems: a review of methodological choices. *International Journal of Life Cycle Assessment*, *22*, 346–363. https://doi.org/10.1007/s11367-016-1156-z

Zhao, G., & Pedersen, A. S. (2018). Life cycle assessment of hydrogen production and consumption in an isolated territory. *Procedia CIRP*, *69*, 529–533. Retrieved from https://doi.org/10.1016/j.procir.2017.11.100

Appendix A: Default *GHGenius* 4.03a Values

Table 16

Default GHGenius 4.03a SMR Input Values in 1996

Parameter	Value
Hydrogen Production Capacity	2000 kg per day (800,000 SCF/day)
Natural Gas	38,298.36 L/ GJ hydrogen
Electrical power required (excluding electricity for compression)	2.37 kWh/ GJ hydrogen
System efficiency in base year 1996	68%
Assumed efficiency improvement rate to 2010	0.20% per year

Table 17

Default GHGenius 4.03a Hydrogen Values in 2000 (Alt Fuels Prod Sheet)

Parameter	SMR	Electrolysis
Electricity, kWh/kg H2	0.33	52.5
Natural Gas, L/kg	5,250	0.0
Total energy, MJ/kg	199.9	189
GHG emissions, g/kg	12,021	11,835

Table 18

GHGenius 4.03a Emission Factors in 2020

Source	Emission Factor	Sheet & Cell #
B.C. Grid Electricity	18, 876 g CO_2e/GJ 67.95 g/kWh	Elec Emissions B62 Elec Emissions C62
B.C. Natural Gas	 50,570 g CO_2e/GJ 8,291 g CO_2e/GJ 58,860 g CO_2e/GJ	Equip Emission Factors Combustion Q25 NG production Q26 Total Q27