How Green is Blue and Green Hydrogen?

Introduction

There is no such thing as a zero-carbon engineered product, including hydrogen. So, what is the carbon intensity[1] for conventionally produced 'grey' hydrogen? How low is the carbon intensity for 'blue' hydrogen which has had some of the carbon emissions captured and sequestered? And what about the carbon intensity of electrolytically produced 'green' hydrogen?

This document is a high-level exercise comparing the carbon intensity for grey, blue, and green hydrogen in Ontario Canada. Before we start, lets describe the hydrogen colour code.

Hydrogen is given a colour based on the carbon intensity associated with producing hydrogen. Grey hydrogen is produced from hydrocarbons, typically from natural gas in a Steam Methane Reformer (SMR[2]). CO_2 produced as part of the SMR process is released to the atmosphere unabated. Blue hydrogen is grey hydrogen but with some of the CO_2 captured. Green hydrogen is produced from water by electrolysis using low carbon intensity electricity.

Chemically the product hydrogen is the same whether called grey, blue, or green. However, in a decarbonizing world the hydrogen market may be willing to pay a price premium for hydrogen carrying a low carbon intensity. So, how green is blue and green hydrogen?

Summary

Direct, or Scope 1[3], emissions resulting from grey hydrogen produced in a Steam Methane Reformer is about 11 tonnes of CO_2 per tonne of hydrogen produced. This emission refers to CO_2 produced because of the SMR operation. Methane when released to the atmosphere is a green house gas that is about 86[4] times as potent as CO_2, referred to as CO_2e. Fugitive methane emissions, although small in terms of tonnes CH_4 per tonne of hydrogen, are significant when considering its green house gas potential. Grey hydrogen can be upgraded to blue hydrogen by capturing and sequestering some of the CO_2 produced by the process and normally released to the atmosphere as part of the SMR process. For this exercise, we assume 85% of Scope 1 CO_2 emissions are captured and not released to the atmosphere. This means that blue hydrogen carries a residual Scope 1 carbon intensity of about 1.5 tonnes CO_2 per tonne of blue hydrogen

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[1] Carbon intensity refers to the carbon emitted due to extracting resources and manufacturing a product including purchased energy such as electricity. There is no such thing as a truly zero engineered carbon product.

[2] Steam methane reforming is by far the most common process used to produce industrial scale volumes of hydrogen.

[3] Scope 1 refers to emissions that are a direct result of an activity. For example, tailpipe emissions from a vehicle. Scope 2 refers to emissions that are indirectly the result of an activity. E.g., emissions from a gas fired power plant providing electricity to enable an activity. Scope 3 emissions refer to all other indirect emissions. E.g. Vehicle emissions are Scope 1 for the vehicle owner, but Scope 3 for the oil company. Scope 1, 2 and 3 emissions are used in setting regulations and in Life Cycle Analysis.

[4] Based on methane 20-year Global Warming Potential which is 86 times CO_2. UNEP. ***Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions***. United Nations Environment Programme Climate and Clean Air Coalition; . https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions.

in addition to the fugitive methane emissions. Fugitive emissions, CO_2e, are not captured although they may be reduced by aggressive leak reduction plus combustion efficiency measures.

Scope 1 emissions resulting from production of green hydrogen are negligible. And since natural gas is not used in the electrolysis process, CO_2e is also practically zero for the process. However, this does not mean that green hydrogen has a zero-carbon intensity. Green hydrogen carbon intensity is dominated by the carbon intensity of the electricity used to produce the green hydrogen. This indirect carbon emission is referred to as Scope 2 emissions.

The Ontario Canada grid has a carbon intensity of about 32 kg of CO_2 per MWh[5] resulting in a carbon intensity of 1.5 tonnes of CO_2 for each tonne of green hydrogen produced in Ontario. Coincidentally in this exercise, the green hydrogen Scope 2 intensity is the same as the Scope 1 carbon intensity for blue hydrogen if fugitive methane emissions are ignored. For a valid comparison of the climatic effects associated with hydrogen production, we need to consider the CO_2 emissions for all three hydrogen varieties, including fugitive methane CO_2e emissions.

Grey and blue hydrogen Scope 2 emissions account for emissions associated with the extraction, processing, and transport of natural gas, including flaring and fugitive methane leaks. In addition, Scope 2 emissions for grey and blue hydrogen include power grid emissions that result from operating the upstream facilities as well as the SMR. Scope 2 emissions associated with generating the electricity required to operate the carbon capture facility must also be included.

Table 1 summarizes carbon intensity for the hydrogen colours. Green hydrogen intensity is dominated by Scope 2 electricity generation emissions while grey and blue hydrogen emissions are heavily influenced by fugitive methane emissions, which are not captured.

Table 1 – Scope 1 and Scope 2 Comparison including Fugitive Methane CO_2e[6]

	Grey H_2	**Blue H_2**	**Green H_2**
Emission	**Tonnes CO_2e per Tonne H_2**	**Tonnes CO_2e per Tonne H_2**	**Tonnes CO_2 per Tonne H_2**
Scope 1 SMR CO_2	11	1.5	De minimis
Scope 1 Fugitive CO_2e	9	10	De minimis
Scope 2 including Carbon Capture electricity + fugitive	1	6.5	1.5
Total Scope 1 and 2 including fugitive CO_2e	21	18	1.5

[5] Based on Ontario 2017 - 2021 annual average electrical grid intensity of 32kg/MWh

[6] Values inn Table 1 were adapted from Table 1 in **How green is blue hydrogen by Robert W. Howarth**, (Cornell & Stanford) and **Mark Z. Jacobson** (Cornell) July 26, 2021, https://onlinelibrary.wiley.com/doi/full/10.1002/ese3.956

Scope 1 Emissions – Grey Hydrogen

Stoichiometrically, the production of 1 tonne of hydrogen using steam methane reforming results in the emission of about 5.5 tonnes[7] of CO_2, a theoretical minimum. However, some of the chemical reactions involved in reforming hydrocarbons, primarily natural gas, are endothermic, meaning heat must be added to the process to make the reactions proceed. The required heat is usually added by burning natural gas. This heat input results in an additional 5 tonnes of CO_2 per tonne of grey hydrogen produced. These 11 tonnes of CO_2 per tonne of grey hydrogen production are direct emissions and referred to as Scope 1 emissions. Scope 1 emissions also include other emissions associated with the grey hydrogen production facility such as building heating, company vehicles etc. For purposes of this paper these emissions are ignored. However, fugitive methane gas is also released.

These fugitive emissions include leaks from valves, joints, connections, rotating equipment seals and as residual unburnt methane in flue gas from combustion processes. Applying a global warming potential of 86 to methane leaks results in an additional 9 tonnes of CO_2e to the grey hydrogen carbon intensity.

Scope 1 Emissions – Blue Hydrogen

Direct CO_2 emissions released from an SMR process come from two sources. One is from the reformer; the other is flue gas from the burner system used to provide heat to drive the process.

Blue hydrogen is distinguished from grey hydrogen by adding CO_2 capture equipment to the SMR facility. Carbon capture equipment is expensive to build and operate and is itself energy intensive. For purposes of this paper, we used an 85% CO_2 recovery efficiency for both the reformer and the flue gas. Recovering higher than 85% is possible, however, the law of diminishing returns applies. As recovery efficiency approaches 100% costs become prohibitive.

In addition to costs to recover the CO_2 we have assumed the captured CO_2 is permanently sequestered. Carbon Capture, Utilization, and Storage (CCUS) is being considered as part of the business approach to carbon capture to offset some of the costs. If utilization involves using the captured CO_2 in a way that will ultimately find its way to the atmosphere, then the net effect would be zero percent effectiveness in reducing the climate impacts of manufacturing hydrogen. Since carbon capture facilities do not capture fugitive methane releases the resulting CO_2e emissions are the same as for grey hydrogen plus an additional tonne of CO_2e per tonne of hydrogen produced resulting from fugitive emissions released from the carbon capture facility.

Scope 1 Emissions – Green Hydrogen

Water is the primary feedstock used to make green hydrogen. No fossil-based feedstock or on-site fuel combustion is involved in the electrolysis process. Therefore Scope 1 emissions resulting

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[7] $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$ and Molecular Weight of CO_2 = 44, MW of 4H2 = 8. Ratio of MW's 44/8 = 5.5

from the production of green hydrogen are practically zero. The project may use fossil fuels for building heating, company vehicles etc. Should that be the case then those emissions would need to be included in the emission intensity assessment for the facility's green hydrogen production. However, the facility could use electric vehicles, electric space heating etc. Should that be the case then the Scope 1 emission intensity for green hydrogen would be de minimis. Again, natural gas is not used directly in the process. Therefore, there are virtually no fugitive methane, CO_2e emissions.

Scope 2 Emissions

Scope 1 emissions are but one part of a carbon intensity assessment. Indirect emissions associated with producing electricity as well as emissions resulting from production of natural gas for fuel and feedstock for the SMR must be considered and referred to as Scope 2 emissions.

Therefore, a carbon intensity comparison of grey, blue, and green hydrogen must include indirect Scope 2 emissions in addition to the direct, or Scope 1, emissions. Again, Scope 2 emissions result from activities, external to the SMR site, required to drive the hydrogen production processes: electricity for green hydrogen and natural gas production and supply for the SMR.

This is important because green hydrogen is always viewed in context of both Scope 1 and Scope 2 emissions. Since Scope 1 emissions for green hydrogen are essentially zero, Scope 2 emissions are used and perhaps without recognizing they are Scope 2.

Scope 2 Emissions – Grey Hydrogen

Indirect emissions associated with the production of the natural gas used in and to drive the SMR process include emissions resulting from the production of natural gas, planned releases (flaring), fugitive methane emissions, emissions associated with pipelines and compressor stations and other CO_2 emissions directly attributable to the natural gas supply[8]. Scope 2 emissions for grey hydrogen are about 1 tonne of CO_2e per tonne of grey hydrogen.

Scope 2 Emissions – Blue Hydrogen

Currently CO_2 capture for upstream emissions associated with production and transport of natural gas is not being contemplated[9]. Therefore, blue hydrogen refers to a grey hydrogen manufacturing facility that reduces its direct, Scope 1, CO_2 emissions, but not Scope 1 fugitive CO_2e or Scope 2 electricity and fugitive CO_2e related emissions. Therefore, the capture efficiency for blue hydrogen is significantly reduced when applying the capture performance over the facility's Scope 1 and Scope 2 emissions and considering fugitive CO_2e emissions.

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[8] **How green is blue hydrogen by Robert W. Howarth**, (Cornell & Stanford) and **Mark Z. Jacobson** (Cornell) July 26, 2021, https://onlinelibrary.wiley.com/doi/full/10.1002/ese3.956

[9] Although carbon capture is not currently being contemplated, significant effort is underway to reduce fugitive methane releases. If successful, reduced methane releases would improve Scope 2 emissions for grey and blue hydrogen.

Including Scope 1 and 2 plus fugitive CO_2e emissions is important when comparing green hydrogen to blue hydrogen because green hydrogen is always viewed in context of both Scope 1 and Scope 2 emissions. Since Scope 1 emissions for green hydrogen are practically zero, Scope 2 emissions are typically assumed and perhaps without recognizing they are Scope 2. This could lead to an improper comparison with blue hydrogen Scope 1 emissions where some of the CO_2 is captured and none of the Scope 1 and Scope 2 fugitive CO_2e emissions are captured.

Capturing CO_2 is highly energy intensive and primarily Scope 2. The estimates on Table 1 included emissions associated with electricity (Scope 2) required to capture and compress CO_2 as well as fugitive emissions for upstream methane production and shipment. Scope 2 emissions for blue hydrogen is about 6.5 tonnes of CO_2e/tonne of hydrogen.

Scope 2 Emissions – Green Hydrogen

Scope 2 emissions associated with pumping and treating the raw feed water to feed the electrolyzers were considered minimal in context of electrolyzer electricity requirements.

Scope 2 emissions resulting from production of green hydrogen depend on the electrical grid CO_2 intensity. The Ontario grid year average intensity over the past five years was between 30 and 35 kg/MW-h. Since the ***HySar***[10] proposed project will draw power only when prices are low the CO_2 intensity will be lower than the year average. However, for purposes of this discussion we used the year average value. Based on a year average intensity of 32 kg MW-h the **HySar** Scope 1 and 2 emissions will be about 1.5 tonnes of CO_2 per tonne of green hydrogen produced.

Scope 3 Emissions

Scope 3 emissions normally involve GHG releases to the atmosphere because of the intended use of the product. Scope 3 emissions resulting from the use of grey, blue, or green hydrogen have been assumed to be the same so were not considered in this discussion.

[10]HySar is a proposed green hydrogen facility to be located in Sarnia – Lambton, Ontario Canada. ***The Business Case for Green Hydrogen in Sarnia Lambton,*** June 2022, Bowman Centre for Sustainable Energy. https://www.bowmancentre.com/