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Life-cycle greenhouse gas emissions of hydrogen as a marine fuel and cost of producing green hydrogen in Brazil

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Summary

In 2018, the International Maritime Organization (IMO) set an initial strategy to halve greenhouse gas (GHG) emissions by 2050 compared to 2008 levels. That strategy is likely to be strengthened in 2023. To achieve that goal, cleaner alternative fuels, such as renewable electrolysis hydrogen, are crucial.

Brazil is considered a potential renewable hydrogen producer given its abundant and potentially expanding renewable energy sources.

This study estimates renewable electrolysis hydrogen production costs and life-cycle GHG emissions for maritime applications in Brazil. We base costs on Brazil's levelized production costs of renewable energy sources; we compare life-cycle GHG emissions to that of conventional fuel marine gas oil (MGO) and among different pathways to produce, transport, store, and use hydrogen in maritime applications.

We find that:

» Brazil has competitive advantages to produce renewable electrolysis hydrogen, given its lower costs in 2020 (US$3.5/kg) compared to other regions, such as European Union (EU) and the United States (US$6.4/kg and US$4.3/kg, respectively);

» Brazilian renewable electrolysis hydrogen (using additional renewable electricity) has 96% lower life-cycle GHG emissions than MGO;

» Renewable electrolysis hydrogen GHG intensity (in g CO_2e/MJ) is almost 80% lower than natural gas SMR hydrogen production with carbon capture and storage (CCS) and 90% lower without it; and

» Significant climate benefits would only be achieved if hydrogen production is powered by additional renewable electricity (80% lower GHG emissions compared to hydrogen produced using grid electricity).

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Robust incentive policies are needed to initially expand hydrogen. Such support would help to overcome technical barriers associated with infrastructure and storage, incentivize maritime applications, and ensure traceability, thus guaranteeing its GHG mitigation benefits.

Introduction/Background

This study explores the cost to produce renewable electrolysis hydrogen in Brazil and its potential maritime use. We performed a life-cycle analysis of its GHG intensity using the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model and estimated its production costs in Brazil. We calculated potential GHG savings of hydrogen produced from renewable electricity, grid-average electricity, natural gas, and natural gas with CCS. We compared Brazil's renewable electrolysis hydrogen costs with estimated costs for other global regions and with fossil-based pathways. Finally, we identified major barriers and opportunities for hydrogen application in Brazil and provided recommendations for Brazil to develop a robust renewable hydrogen supply.

Maritime transport is crucial to global trade and economic development. However, the sector also contributes to global climate change, producing around three percent of global carbon dioxide (CO_2) emissions; this is equivalent to the sixth biggest emitter country in the world (Englert et al., 2021; Faber et al., 2020; Schlanger, 2018). In recent years, the sector has been under increasing pressure to reduce GHG emissions. In 2018, the IMO pledged to reduce annual GHG emissions from international shipping by at least half by 2050 compared to 2008 levels (Lakshmi, 2018). To achieve this goal, besides optimized operations and energy efficiency measures, alternative low- or zero-carbon fuels will be crucial (Florentinus et al., 2012; International Energy Agency, 2021b).

Alternative maritime transportation energy sources or fuels include batteries (X. Mao et al., 2020), biofuels (Zhou, Pavlenko, et al., 2020), and synthetic fuels such as hydrogen (Comer , Stolz, et al., 2022; Georgeff et al., 2020; X. Mao et al., 2020). To be suitable for achieving global and sectorial climate goals, such alternatives must generate low- or zero-CO_2-equivalent life cycle emissions, on a well-to-wake (WTW) basis (Comer, Stolz, et al., 2022). Among possible alternative energy sources, hydrogen is promising especially because of its potentially low climate impact. Because it contains no carbon, it emits no carbon when it burns, though it does produce air pollution in the form of nitrogen oxides (NO_x). When produced from water electrolysis powered by renewable electricity, the volume of upstream GHG emissions drops (Atilhan et al., 2021). When used in a fuel cell, it emits only water.

Hydrogen is most efficiently used in fuel cells, which convert a fuel's chemical energy into electricity, although it can also be used in adapted combustion engines (U.S. Department of Energy, 2019). Fuel cells have a completely different technology than internal combustion engines (ICEs) currently used by the world's shipping fleet; their adoption would require a complete remodeling of propulsion systems. In addition, efficiently storing and transporting hydrogen is challenging, because it needs to be compressed or liquefied (DNV, 2021; Van Hoecke et al., 2021). Further, despite its high calorific value by mass, hydrogen has low energy density by volume; fuel storage is massive and requires more space than conventional fuels (DNV GL, 2019).

Hydrogen can be generated from both renewable and non-renewable sources. Existing worldwide production comes mainly from fossil fuel sources, such as natural gas (59%), heavy oils and naphtha (21%), and coal (19%); only 0.03% comes from water electrolysis (International Energy Agency, 2021a). Figure 1 color codes hydrogen production pathways. Grey hydrogen refers to hydrogen produced from natural gas, blue hydrogen is produced from natural gas with CCS (IRENA, 2019), and green hydrogen refers to hydrogen produced from water electrolysis using renewable electricity, particularly wind and solar (IRENA, 2022b). The energy sources and feedstocks used to produce hydrogen directly affect its life-cycle GHG intensity. Using fossil feedstocks and grid electricity to produce hydrogen increases its direct and indirect life-cycle GHG emissions. Therefore, it is important to ensure the availability of renewable electricity to produce green hydrogen.

	GREY HYDROGEN	**BLUE** HYDROGEN	**GREEN** HYDROGEN
Process	Steam Methane Reform (SMR) or Gasification	Steam Methane Reform (SMR) or Gasification with carbon capture	Electrolysis
Source	Natural gas (methane) or Coal	Natural gas (methane) or Coal	Renewable electricity

Figure 1. Color-Coded Hydrogen Production Pathways

Renewable electrolysis hydrogen technology could be suitable for international maritime transportation, complementing other alternative energy sources and energy efficiency measures. However, its costs could be as much as triple fossil-based hydrogen (IRENA, 2022b; Gurlit et al., 2021). In this sense, countries capable of generating cheap renewable electricity are best positioned to produce competitive green hydrogen (IRENA, 2022b). Brazil, then, could be a potential renewable electrolysis hydrogen producer given its abundant renewable energy sources and the predicted expansion of wind- and solar-based electricity generation (Ministério de Minas e Energia & Empresa de Pesquisa Energética, 2021b). Renewables account for approximately 85% of Brazil's domestic electricity supply, which is composed of the sum of national production plus imports. Hydropower represents the highest share of national electricity supply (65%), followed by biomass (9%), and wind (9%). Solar photovoltaic (PV) generation accounts for less than 2% of domestic supply, but significant recent additions to installed capacity indicate its potential expansion (Ministério de Minas e Energia, 2021).

Currently, the main demand for hydrogen in Brazil comes from oil refineries and fertilizer production (Empresa de Pesquisa Energética, 2022). As of 2022, US$22 billion in investments in the construction of renewable hydrogen plants in Brazil had been announced, all in ports in the Northeast region (Bnamericas, 2021; Chiappini, 2021; Uchôa, 2021). Such ports combine numerous strategic advantages for the development of the green hydrogen supply chain, such as favorable export logistics, proximity to industrial zones (where companies are interested in decarbonizing operations and/or contributing to solutions for other industries), and access to wind and solar power sources. Therefore, before its maritime application, renewable hydrogen would face competition for use in other sectors, such as mining (iron ore production) or the production of renewable synthetic chemicals, fuels, and green ammonia (Santos & Ohara, 2021). If all the announced projects succeed, Brazil could become a major global player in the emerging green hydrogen market.

Hydrogen as marine fuel

The latest version of Mapping of Zero Emission Pilots and Demonstration Projects for the maritime industry shows an increasing focus on hydrogen and hydrogen-based fuels (Fahnestock & Bingham, 2021). As of August 2022, only eight hydrogen-capable ships are expected to be built in 2022-2026, according to the 2022 World Fleet Register (Clarksons Research, 2022). Among them, three small ships were designed for hydrogen-only application. Additionally, 16 pilot projects for hydrogen fueled ships are in development or have been completed (Comer, Stolz, et al., 2022). Of those, 12 use hydrogen in fuel cells and 4 use hydrogen in combination with MGO in ICEs.

Hydrogen can be used on-board as a marine fuel either in fuel cells or adapted combustion engines. The most significant technical barrier to using hydrogen as a fuel is neither production nor end-use, but storage, given its low volumetric energy density requires cryogenic or pressurized storage systems (Van Hoecke et al., 2021). The development of novel bunkering infrastructure and safety monitoring also pose challenges to hydrogen's application in maritime transport (Van Hoecke et al., 2021).

Hydrogen use in fuel cells

Fuel cell technology has received increasing interest as an alternative power supply system for ships. Fuel cells convert chemical energy to electricity through electrochemical reactions that use molecular hydrogen and oxygen. For ships, fuel cell systems connected to electric motors convert electricity into mechanical work for propulsion. Electricity and water are the only products of this reaction, with no direct GHG or air pollutant emissions. Fuel cells also reduce noise and vibrations that impact marine ecosystems (Balcombe et al., 2019; Tronstad et al., 2017).

Fuel cells are generally classified according to their electrolyte types but can also be categorized based on their working temperatures, used fuel types, or working areas (mobile/stationary) (Inal & Deniz, 2020; Tronstad et al., 2017). The primary types of fuel cells are alkaline (AFC), phosphoric acid (PAFC), molten carbonate (MCFC), solid oxide (SOFC), and proton exchange membrane (PEMFC) (see Table 1, which is based on Inal & Deniz, 2020). The efficiencies of fuel cells vary between 50-60%. For high-temperature fuel cells, such as MCFC and SOFC, efficiency rises if waste heat is recovered (Tronstad et al., 2017). The electric motors used for propulsion are highly efficient (~95%), and, when combined with efficient fuel cells, are more advantageous than ICEs. For example, fuel cells require 44% less fuel than diesel generators and micro gas turbines to produce the same power output (Balcombe et al., 2019). However, space requirements for fuel cells could be challenging (particularly for smaller ships), as they need almost twice the space of ICEs (Bourne, 2019).

Table 1. Fuel Cell Types

Fuel Cell Type	Fuels	Efficiency (%)	Operation temperatures (°C)
Alkaline (AFC)	H_2	50-60	50-230
Phosphoric Acid (PAFC)	H_2 Natural Gas Diesel	40-50	150-220
Molten Carbonate (MCFC)		30-70	600-700
Solid Oxide (SOFC)		40-70	500-1000
Proton Exchange Membrane (PEMFC)	H_2	40-60	50-130

Hydrogen use in ICEs

ICEs have been used in transportation for more than 100 years. Most contemporary marine fleets use diesel engines. They are typically categorized as slow- (large vessel propulsion), medium- (propulsion or auxiliary power generation), or high-speed (auxiliary power generation and for the propulsion of smaller vessels) engines. In the past 20 years, dual-fuel and pure gas ICEs have been introduced for propulsion and auxiliary power of marine vessels. Dual-fuel engines are diesel engines that can run on both gaseous and liquid fuels (DNV GL, 2019).

Hydrogen has different uses in ICEs. The first is combustion in dual-fuel engines (operating in gas mode) with minor adaptations. So far, tests of this use show efficiencies ranging from 35-50% (DNV GL, 2019; Hyde & Ellis, 2019). The second is co-feeding with diesel in regular marine diesel engines. Given its high auto-ignition temperature, pure hydrogen cannot be directly used; combined with diesel in mixtures of up to 80% (energy basis) it brings efficiencies of ~30% (Hyde & Ellis, 2019). Contrary to fuel cell systems, hydrogen ICEs can be fueled with non-purified hydrogen, which may significantly reduce costs (Onorati et al., 2022). However, hydrogen use in ICEs leads to NO_x emissions (unlike its use in fuel cells).

Hydrogen storage on ships

The principal physical challenge for hydrogen as a marine fuel is neither production nor end use, but storage. On a mass basis, hydrogen is an excellent energy carrier; its lower heating value (LHV) is almost three times superior to MGOs (120 MJ/kg vs. 43 MJ/kg). However, hydrogen is light; its volumetric energy density is 3500 times lower than MGOs in atmospheric conditions (0.01 MJ/L vs; 35 MJ/L) (DNV GL, 2019; Van Hoecke et al., 2021). To store it efficiently, it must be compressed (CH_2) or liquefied (LH_2).[1] Table 2 compares hydrogen and MGO properties under different conditions (see Air Liquide, 2022; DNV GL, 2019; Van Hoecke et al., 2021).

Table 2. Hydrogen and MGO Properties

	Density (kg/m³)	Energy density, mass (MJ/kg)	Energy density, volume (MJ/L)
H_2 (atmospheric conditions)	0.09	120	0.01
CH_2 (at 700 bar)	42	120	5.0
LH_2 (cryogenic at -253 °C)	71	120	8.5
MGO (atmospheric conditions)	860	43	35

Compressed hydrogen

Hydrogen compression is the most developed and widely used storage method (Van Hoecke et al., 2021). CH_2 typically requires high-pressure tanks (350-700 bar), similar to conventional high-pressure natural gas storage tanks (Baetcke & Kaltschmitt, 2018; U.S. Department of Energy, 2021). Tanks with higher pressures (~700 bar) can have increased storage capacity but could cost 10 times more than low pressure tanks (Van Hoecke et al., 2021). Additionally, even at such high pressure, hydrogen energy density only reaches about 5 MJ/L, significantly lower than MGO (Table 2). Thus, CH_2 requires larger storage space on ships compared to MGO. Nevertheless, CH_2 can fit into a variety of configurations and tank sizes based on vessel's dimensions (Comer, Stolz, et al., 2022). Additionally, compared to LH_2, CH_2 takes up more available weight and space due to its lower energetic density.

There are two main advantages of CH_2 storage tanks: no thermal management, such as liquefaction or cryogenic storage, is required; and their weight is more manageable than the cryogenic tanks needed for LH_2. Their most significant disadvantages are their high operating pressures and the consequent need for strong materials to prevent hydrogen diffusion over time (Baetcke & Kaltschmitt, 2018).

1 Hydrogen could also be stored in materials such as liquid organic hydrogen carriers (LOHC) or materials (metal hydrides, activated carbons, etc.) (Baetcke & Kaltschmitt, 2018; U.S. Department of Energy, n.d.)

Liquid Hydrogen

LH_2 is an alternative to store hydrogen with high volumetric energy density. Liquid products offer several technical handling benefits over compressed gases. Liquid hydrogen's principal challenge comes from the low temperatures it requires; it condenses at temperatures as low as -253 °C (Baetcke & Kaltschmitt, 2018; Depken, et al., 2022). Thus, LH_2 tanks must be made of super insulating materials and have a spherical design to lower surface-to-volume ratio, given that thermodynamic losses are directly related to external surface area (Baetcke & Kaltschmitt, 2018; Georgeff et al., 2020).

Additionally, even in liquid form, hydrogen's volumetric energy density (8.5 MJ/L) is almost four times lower than MGO (35 MJ/L) (see table 2). Thus, larger volumes of LH_2 are needed to replace MGO on ships, not accounting for the thickness of tank insulation materials. Although the maritime industry has experience with cryogenic fuels given the growing use of liquefied natural gas (LNG), the challenges of using LH_2 are larger.

Bunkering

Hydrogen's storage mode directly affects its bunkering method. CH_2 stored at port can be transferred to ships in two ways: pressure balancing or compression. In the first method, CH_2 is stored at a higher pressure than the ship requires (for example, ships requiring hydrogen at 350 bar would need it stored at 500 bar in the port) (Hyde & Ellis, 2019). Thus, hydrogen naturally flows into a ship's storage tanks. This method requires considerable port storage capacity given that much of the storage stays inaccessible (when port storage pressure drops below 350 bar, for example, it is impossible to fill a ship to 350 bar) (Hyde & Ellis, 2019). In the second method, a compressor moves CH_2 from a low-pressure port storage site to the ship. This method allows better control of hydrogen flow but requires higher equipment expenses.

Liquid hydrogen stored at the port can be transferred to ships using cryogenic pumps, a technology already used in LNG bunkering but that needs modifications (for example, LH_2 would need lower storage temperatures and presents higher risk of leakage) (Hyde & Ellis, 2019; Nerheim et al., 2021). Georgeff et al. (2020) evaluated different alternatives for LH_2 bunkering, not only considering its stationary storage at ports (port-to-ship bunkering, PTS), but also transfer from trucks (truck-to-ship, TTS) and from refueling vessels (ship-to-ship, STS). These three methods differ most based on fuel transfer rates (Georgeff et al., 2020).

Potential hazards

Hydrogen is a colorless, odorless gas almost 14 times lighter than air. Thus, it rapidly spreads in the air and easily permeates materials. Vaporized hydrogen is highly flammable. Hydrogen flame is invisible (making it difficult to detect) and reaches temperatures of up to 2318K (~2045 °C). Explosion risks can occur at low concentrations (18-49%vol) (Depken et al., 2022). And although hydrogen is nontoxic, it can provoke asphyxia if it displaces environmental oxygen to concentrations below 16% (Depken et al., 2022; DNV, 2021; Van Hoecke et al., 2021).

Therefore, when storing hydrogen in confined spaces such as ships, safety systems must be carefully designed with strategically placed sensors and ventilation systems. Additionally, the cryogenic storage of LH_2 requires special materials to support colder temperatures. On-board cryogenic liquid spills can lead to cold fractures and damage a ship's hull. Additionally, the formation of hydrogen clouds after spills increases explosion and asphyxiation risks, endangering crew (Depken et al., 2022; DNV, 2021; Van Hoecke et al., 2021).

Methodology

This study estimated the production costs for green hydrogen in Brazil and compares the life-cycle GHG emissions of renewable electrolysis hydrogen with other hydrogen pathways (Figure 2) such as natural gas SMR hydrogen, natural gas SMR with CCS hydrogen, and grid-average electrolysis hydrogen and also according to different storage modes (compressed vs. liquefied).

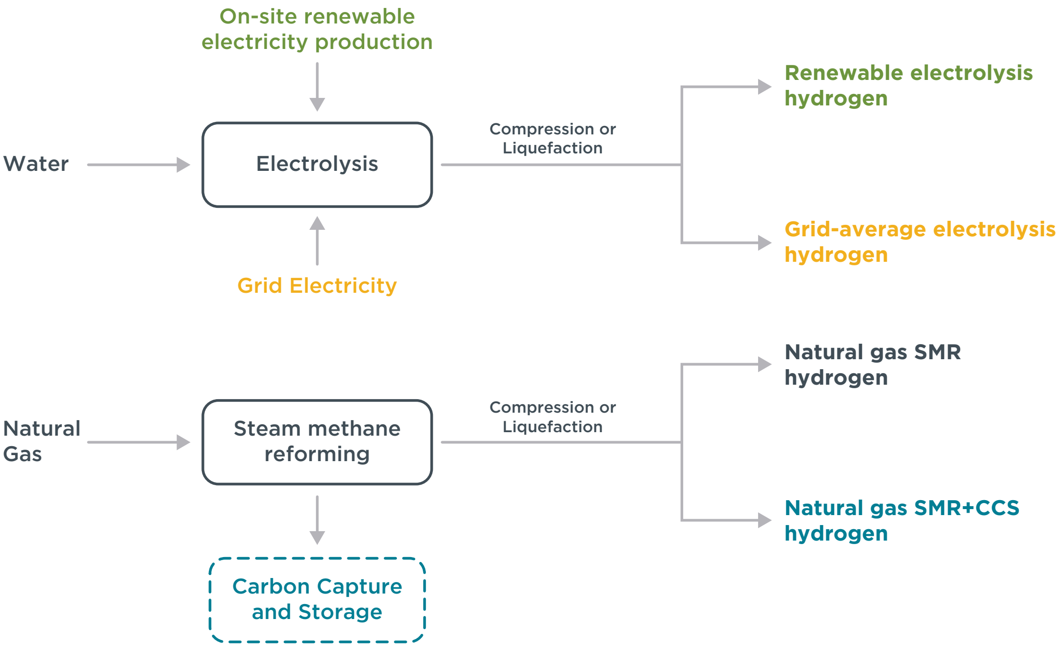

Figure 2. Hydrogen Production Pathways

Life-cycle GHG emissions of hydrogen as a marine fuel

We estimated full life-cycle GHG emissions (WTW) from five hydrogen pathways. For SMR-based pathways, we assumed natural gas was transformed in a steam methane reformer into hydrogen, which was liquified using national grid electricity and transported by truck to storage. For pathways with CCS, we considered the additional CCS step at the gas reformer. For hydrogen made by electrolysis, we assumed two sources of electricity: national average grid (grid-average electrolysis hydrogen) or additional renewable (renewable electrolysis hydrogen). For renewable hydrogen, we modeled both LH_2 and CH_2.

For all pathways, we applied 100-year and 20-year global warming potential factors (GWP100 and GWP20) for converting climate impacts of methane and N_2O on the CO_2-equivalent (CO_2e) basis. Using GWP20 (together with GWP100) is essential for understanding the near-term impact of short-lived GHGs such as methane. We applied GWP factors from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report 6 (AR6).

To estimate GHG emissions of hydrogen pathways, we used the GREET model (Argonne National Laboratory, 2020). GREET models the full life cycle (WTW) of various transportation fuels and offers the flexibility to change underlying assumptions while consistently estimating emissions for multiple fuel pathways. The WTW analysis included feedstock extraction, fuel production, transportation, and combustion emissions. Since it produces only water vapor, we attributed zero GHG emissions to hydrogen combustion in fuel cells. For natural gas SMR+CCS hydrogen, we included energy use and associated emissions for the CCS process. We reduced the carbon capture rate from GREET's default of 90% to 55% to reflect real-world industrial practices (Zhou, Swidler, et al., 2021).

We adjusted some of the underlying GREET data to better reflect the GHG intensity of hydrogen production in Brazil, such as the electricity mix of the Brazilian grid (Table 3) and natural gas production assumptions, based on the 2020 Brazilian Energy Balance (EPE, 2021a). We kept default GREET values for transportation-related emissions. Potential hydrogen leaks were not accounted for in WTW emissions. However, recent research suggests that leaks could lead to indirect GHG emissions, with hydrogen itself possessing an estimated GWP100 of approximately 11 (Warwick et al., 2022).

Table 3. Electricity Grid Assumptions

Electricity generation mix	GREET default (U.S. Mix)	Brazil
Residual oil	0%	2%
Natural gas	40%	8%
Coal	20%	3%
Nuclear power	20%	2%
Biomass	0%	9%
Hydroelectric	7%	65%
Wind	9%	9%
Solar PV	2%	2%
Others	0%	0%

Renewable electrolysis hydrogen production costs

We estimated renewable electrolysis hydrogen production costs using a discounted cashflow model built in previous studies (Christensen, 2020; Zhou & Searle, 2022). The model incorporates the capital costs associated with both renewable electricity and hydrogen production, operating costs, capacity factors, and conversion yields, to estimate levelized costs of production. We expect decreasing capital costs and increasing capacity factor and electrolysis efficiency to drive down the cost of renewable electrolysis hydrogen in the future. We projected future renewable electrolysis hydrogen cost using different scenarios—mid-level, pessimistic, and optimistic—to account for uncertainties in those factors. To assess the use of hydrogen for maritime, we incorporated additional costs for compression to 350 bar or liquefaction. While we modeled compression costs using our estimated renewable electricity cost, liquefaction costs were based on a literature review.

We also updated the model with Brazil-specific data. Specifically, we collected the capacity factor of solar and wind power plants in Brazil in 2020 (Operador Nacional do Sistema Elétrico, 2022) as 23% and 44% respectively. The capacity factor determines how often a solar or wind renewable generator could operate, thus impacting the production cost of renewable electricity. Table 4 shows estimated solar and wind levelized production costs. While we modeled both wind and solar electricity costs, we input the cheaper cost (wind), into the green hydrogen model.

Table 4. Estimated Wind and Solar Production Costs

Year	Solar cost per MWh US$/R$	Wind cost per MWh US$/R$
2020	53 / 284	33 / 177
2030	34 / 182	26 / 139
2050	26 / 139	20 / 107

We also collected electricity transmission and distribution fees (R$128 per MWh) and water prices (R$4.25 per cubic meter) for industrial users in 2021 in Brazil (ANEEL, 2022; Sistema Nacional de Informações sobre Saneamento, 2022); we assumed these costs would remain constant in future years due to limited cost projection information. See Zhou and Searle (2022) for other model assumptions and data inputs, such as capital costs of renewable electricity and electrolysis.

Results

Comparison of life-cycle GHG emissions of renewable electrolysis hydrogen

This section presents the results of the life-cycle GHG emissions of the extraction, production, transportation, and combustion of five production pathways: natural gas SMR; natural gas SMR+CCS; grid-average electrolysis liquified hydrogen; renewable electrolysis compressed hydrogen; and renewable electrolysis liquified hydrogen in Brazil. Results for the GWP100 and GWP20 time horizons demonstrate hydrogen's long- and short-term climate impacts.

Figure 3 presents the results. The bars represent the WTW GHG emissions using GWP100, while the triangles represent GWP20 results. Natural gas SMR hydrogen has the highest WTW CO_2e emissions (96 g CO_2/MJ for GWP100), 7% higher than WTW GHG emissions generated by MGO (90 g CO_2e/MJ). Natural gas SMR hydrogen produces significant GHG emissions, varying from 11 to almost 14 kg of CO_2e per kg of hydrogen, depending on the feedstock used (Moberg & Bartlett, 2022). On a 20-year horizon, its GHG emissions can be as high as 108 g CO_2e/MJ. Adding CCS to the production cycle (SMR+CCS hydrogen) reduces WTW GHG emissions by 43% (51 g CO_2e/MJ), GWP100 basis, compared to MGO.

Electrolysis hydrogen GHG emissions vary depending on the electricity source. When we applied Brazil's national grid electricity (with its 87% share of non-fossil energy), WTW GHG emissions were higher than those from natural gas SMR+CCS hydrogen on a 100-year horizon (54 g CO_2e/MJ vs. 51 g CO_2e/MJ for GWP100). On a 20-year horizon, emissions were slightly lower for grid-average electrolysis hydrogen (60 g CO_2e/MJ vs. 63 g CO_2e/MJ), because of the short-term climate impact of methane emissions from natural gas extraction.

The lowest GHG emissions among all pathways were estimated from renewable electrolysis hydrogen. Our results showed that producing compressed renewable electrolysis hydrogen has near-zero WTW GHG emissions (4 g CO_2e/MJ for both GWP100 and GWP20), which reduces emissions by 96% compared to MGO. Producing liquid renewable electrolysis hydrogen can slightly increase emissions compared to the gaseous option since additional energy is needed for liquefaction (11 g CO_2e/MJ and 12 g CO_2e/MJ for GWP100 and GWP20 respectively). However, renewable electrolysis hydrogen still generates 88% less WTW GHG emissions than MGO, 89% less than natural gas SMR hydrogen, 79% less than natural gas SMR+CCS hydrogen, and 80% less than grid-average electrolysis hydrogen. This highlights the importance of using additional renewable electricity for hydrogen production.

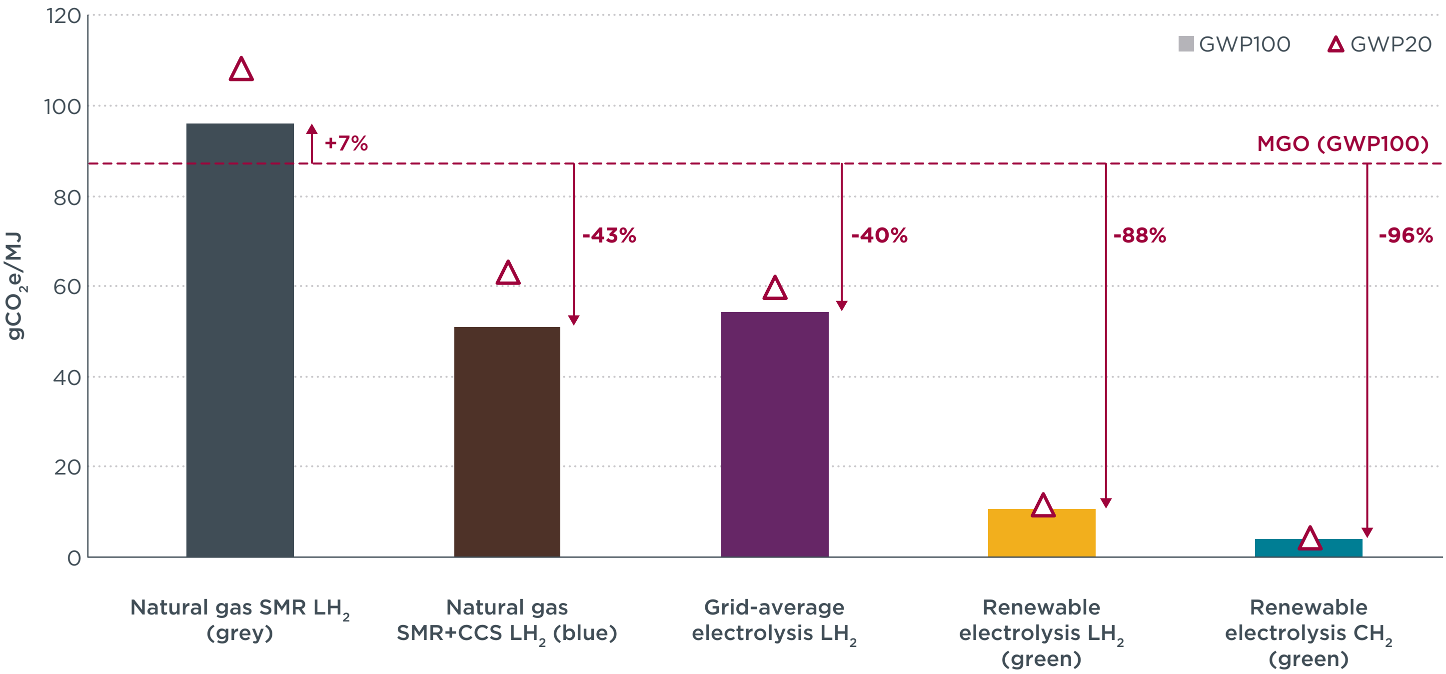

Figure 3. Hydrogen Pathway Life-cycle GHG Emissions

Renewable hydrogen production costs

Table 5 shows estimated levelized production costs of renewable electrolysis hydrogen in Brazil, excluding additional compression or liquefaction costs. We estimated costs to decrease from US$3.4 (R$18[2]) per kg hydrogen in 2020 to US$1.3 (R$7) per kg hydrogen in 2050, based on the mid-level cost scenario. Decreasing production costs are a combined result of decreasing renewable electricity costs and decreasing electrolyzer costs as the technology improves and the market matures.

Table 5. Production Costs Excluding Compression or Liquefaction

Year	2020 US$/kg H_2	2020 R$/kg H_2
2020	3.4	18
2030	2.6	14
2050	1.3	7

We estimated that compressing hydrogen to 350 bar would cost US$0.5 (R$2.7) more per kg. Based on previous studies, liquefaction would add about US$1.5 (R$8) per kg (NCE Maritime CleanTech, 2016; IRENA, 2022a). Table 6 shows total costs with compression or liquefaction.

Table 6. Production Costs Including Compression and Liquefaction

Year	2020 US$/R$/kg CH_2	2020 US$/R$/kg LH_2
2020	3.9 / 21	4.9 / 26
2030	3.1 / 17	4.1 / 22
2050	1.8 / 10	2.8 / 15

2 This study assumed an exchange rate of US$1 to R$5.36.

Discussion

Life-cycle assessment results showed that using renewable hydrogen in maritime transportation reduces WTW GHG emissions up to 96% compared to MGO. Using renewable electricity instead of natural gas to produce LH_2 reduces GHG emissions almost ninefold (from 96 to 11 g CO_2e/MJ). When CCS was considered for natural gas-based hydrogen, renewable electrolysis LH_2 presented almost fivefold lower emissions (from 51 to 11 g CO_2e/MJ). Even with the relatively clean electricity generation sources, using Brazilian grid electricity to produce hydrogen resulted in a fivefold increase in WTW GHG emissions compared to renewable hydrogen (from 11 to 54 g CO_2e/MJ). This is because of energy conversion losses during electrolysis. While we estimated that CCS-based hydrogen has lower emissions than grid-electrolysis hydrogen (51 vs. 54 g CO_2e/MJ), the expected increase in the use of renewable energy sources for Brazilian electricity production (Ministério de Minas e Energia & Empresa de Pesquisa Energética, 2022) would narrow this gap and make grid-electrolysis hydrogen a cleaner alternative.

Based on our analysis, it appears Brazil could produce renewable hydrogen at relatively low costs. Figure 4 shows the cost comparison among Brazil, the United States, and the European Union (Zhou & Searle, 2022; Zhou, Searle et al., 2022). The bars represent mid-level green hydrogen production costs, and the error bars indicate possible cost ranges in Brazil. The orange and brown diamonds show mid-level renewable-electrolysis hydrogen production costs in the United States and European Union, respectively. Among these three regions, we estimated the lowest hydrogen production cost in Brazil. This is justified by Brazil's more abundant renewable resources (i.e., higher capacity factor), leading to lower levelized renewable electricity production costs. Even considering the higher end of the cost range (top of the error bars) that is due to higher renewable electricity and electrolyzer costs, Brazil's renewable hydrogen costs are still much lower than in the European Union and only slightly higher than in the United States.

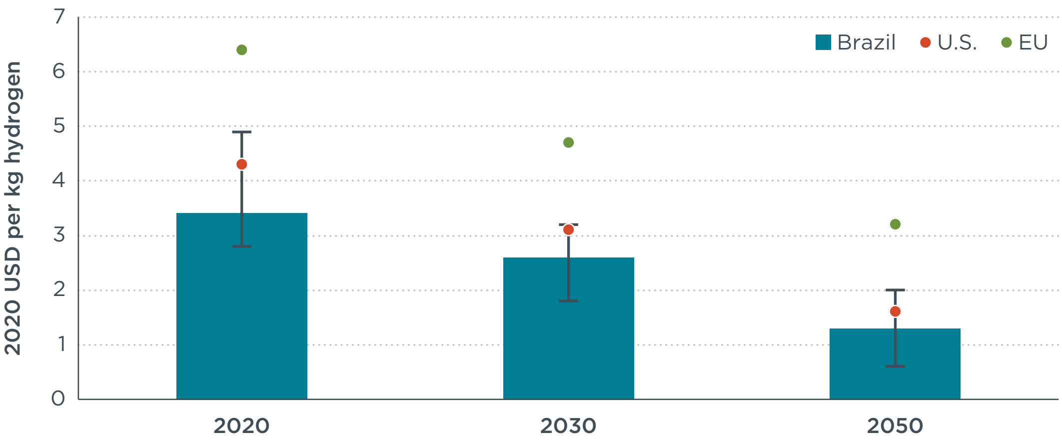

Figure 4. Production Costs in Three Major Regions

The cost of natural gas-based hydrogen produced in Brazil ranges from US$1-1.5 per kg (Empresa de Pesquisa Energética, 2022), almost threefold lower than our estimates for renewable hydrogen costs in 2020 and 2030 and comparable to the 2050 estimate. Natural gas SMR+CCS hydrogen costs are about US$0.6-1.1 per kg more than conventional natural gas-based hydrogen (Baldino et al., 2020; S. Mao et al., 2021). Estimates presented by the Brazilian Energy Research Company (EPE) reported CCS-based hydrogen costs of about US$2 per kg in 2020 (Empresa de Pesquisa Energética, 2021, 2022). While this lower than the 2020 renewable hydrogen cost estimate, its competitive margin is smaller until 2050.

Combining our cost and GHG emissions estimates, we calculated abatement costs for hydrogen relative to MGO. Considering MGO's price of US$1 per kg (2022 average) and life-cycle GHG emissions of 90 g CO_2e/MJ, the abatement costs of natural gas SMR+CCS and renewable electrolysis LH_2 are US$152 and US$221 per ton of CO_2e, respectively, and US$108 per ton of CO_2e for renewable CH_2 (based on 2020 cost estimates). However, it is expected that renewable electrolysis LH2 becomes more competitive than natural gas SMR+CCS LH_2 in the long term. Abatement costs for grey and grid-based hydrogen were not estimated. Grey hydrogen has higher life-cycle GHG emissions compared to MGO (96 g CO_2e/MJ vs. 90 g CO_2e/MJ). Using grid electricity to make electrolysis hydrogen is more expensive than using renewable electricity in Brazil and registers higher emissions; grid-hydrogen is, therefore, less attractive from the perspective of cost-abatement.

We found that significant GHG reductions would only be achieved if hydrogen production were powered by additional renewable energy plants. Even with an increased share of renewables in Brazil's grid, if the renewable electricity supply cannot sustain demand across multiple sectors, electricity would be diverted from existing uses to power green hydrogen production. Each unit of electricity displaced would require substitution by other sources of electricity, which could include fossil fuels. This could make renewable electrolysis hydrogen produced without additionality requirements more similar in its *de facto* WTW emissions to grid-average electrolysis hydrogen. Therefore, hydrogen traceability would guarantee its GHG reduction benefits and certification is essential to ensure that renewable hydrogen is being produced using additional, renewable electricity without causing unintended displacement effects (Malins, 2019). Due to the high conversion losses of hydrogen production, diverting renewable electricity towards its production can have a disproportionate effect, as the conversion losses from electrolyzers mean that hydrogen production consumes approximately 50% more electricity than the energy content of the finished fuel.

Further, to meet the same energy requirements, a ship must consume a greater volume of LH_2 than MGO, given hydrogen lower volumetric energy density. For example, for 1 kWh of energy output, the required volume of LH_2 is 7.2 times greater than MGO[3]. If MGO is replaced by grid-based hydrogen, the GHG emissions for each kWh of energy output would be even higher than for using MGO (3,322 g CO_2e for grid-based hydrogen vs. 3,150 g CO_2e for MGO) (see figure 3). Consequently, replacing MGO for fossil- or grid-based hydrogen could cause an increase in emissions on a WTW basis.

Storage modes also influence renewable hydrogen emissions. Compressed green hydrogen has the lowest WTW CO_2e emissions among all pathways modeled (4 g CO_2e/MJ), being almost three times lower than its liquefied form (11 g CO_2e/MJ). We assumed grid electricity as the energy source for compression and liquefaction. Thus, CH_2 registered lower emissions because electricity demand is lower than for liquefying hydrogen. Compression is currently the main hydrogen storage method, but for maritime applications, its lower energy density compared to LH_2 would require more storage space onboard ships.

Furthermore, considering different GWP factors shows the contribution of short-lived GHG in hydrogen's mitigation potential. Hydrogen production pathways that use natural gas as feedstock (natural gas SMR and natural gas SMR+CCS) registered an increase of up to 13% and 24% in WTW GHG emissions, respectively, on a GWP20 basis compared to GWP100. This is explained by methane emissions in natural gas extraction; methane is a powerful GHG with a GWP approximately 30 times greater than CO_2 over 100 years (GWP100) and more than 80 times greater over 20 years (GWP20).

3 We estimated fuel demand for LH_2 and MGO using Equation 1 in X. Mao et al. (2020). We considered the energy density of hydrogen and MGO as 1,332 and 10,413 kWh/m3, respectively, and efficiencies of 54% and 50% for fuel-cells and ICEs (Comer, 2019).

However, despite the GHG savings of renewable hydrogen, some studies suggest that hydrogen leakage may impact climate. Atmospheric hydrogen venting or leakage could partially offset its climate benefits. Despite being nontoxic and noncorrosive, hydrogen is a short-lived, indirect GHG gas that impacts atmospheric composition, thus contributing to global warming (Ustolin et al., 2022; Warwick et al., 2022).

Despite cost advantages and climate benefits, there are technical, market, and regulatory challenges to the development of renewable electrolysis hydrogen production and its application as a marine fuel. Technical challenges are mainly associated with storage, the establishment of maritime bunkering infrastructure, and safety. Although hydrogen can be used in adapted combustion engines, it is most efficiently used in fuel cells; this would require remodeling of ship propulsion systems and bunkering infrastructure. Also, finding efficient ways to store and transport hydrogen is challenging, because it needs to be compressed or liquefied; this demands significant amounts of energy, increases costs, and requires appropriate infrastructure. Further, its very low volumetric energy density means that storing compressed or liquefied hydrogen aboard ships requires at least 4-7 times more space than petroleum-based marine fuels, respectively. Hydrogen safety concerns call for the development of updated guidelines and standards, especially for the large-scale production, storage, and transport required for maritime applications.

Additionally, long-term price and demand uncertainties hamper investment in the large-scale projects that would drive hydrogen costs down and prove its applicability in the sector. Further, certification, especially on renewable electricity additionality, is needed to avoid potential indirect effects of hydrogen production, guaranteeing its traceability, and ensuring its GHG reduction benefits. Additional challenges are associated with the infrastructure required to provide additional renewable electricity supply, its climate impacts, and rights of way.

Conclusions

To understand Brazil's role in providing renewable hydrogen for maritime applications, this study performed economic and life-cycle analyses to determine renewable electrolysis hydrogen production costs and its potential GHG savings in Brazil. Renewable hydrogen is a promising alternative fuel to decarbonize international maritime transportation, especially because of its zero direct GHG emissions and its potential for low life-cycle GHG emissions.

Brazil is poised to become a world leader in renewable hydrogen production given its large renewable energy resources and potential to develop additional renewable electricity (which would enable hydrogen production at lower costs compared to other regions). Renewable electrolysis hydrogen costs in Brazil are expected to drop 60% from 2020 to 2050, reaching US$1.3/kg H_2 (R$7/kg H_2). However, to ensure that hydrogen use on-board ships provides GHG reduction benefits, it must be evaluated across the entire life cycle. Our analysis showed the mitigation benefits of renewable electrolysis hydrogen use in maritime transport, reducing GHG emissions by up to 96% compared to MGO. Among all the hydrogen pathways we assessed, renewable electrolysis hydrogen offers the most climate benefits compared to existing marine fuels. Despite its zero emissions onboard, natural gas-based hydrogen led to higher life-cycle GHG emissions than current marine fuels. Also, using grid electricity diminishes hydrogen's GHG benefits, even with Brazil's low-emission grid, which points to the need for hydrogen traceability and certification to ensure electricity used for its production is both renewable and additional.

Despite hydrogen's promising outlook and potential competitiveness, the development of energy policies dedicated to hydrogen in Brazil are uncertain. The expected increase in the share of renewables in the Brazilian electricity mix strategically positions the country in the renewable hydrogen market (including in the maritime transport sector). Accordingly, strategies to address green hydrogen's specific challenges in Brazil are needed. For example, robust incentive policies with well-grounded roadmaps would generate the initial expansion necessary for hydrogen to benefit from scale gains that would make it more economically attractive and define its priority uses. Such policies applied to promote renewable hydrogen in Brazil and its use in maritime transportation would incentivize research and development, bring financial incentives, and help reach the IMO's decarbonization targets.

Future work

Future work can illuminate Brazil's potential for producing green hydrogen for use in maritime shipping. Such analyses could include:

» Mapping Brazil's green hydrogen production potential to identify promising production sites considering its maritime use;

» Comparing Brazil's green hydrogen GHG emissions performance to fossil and renewable LNG, methanol, and ammonia on a WTW basis, considering different scenarios for alternative marine fuels utilization in the country, similar to previous studies (Comer, O'Malley, et al., 2022); and

» Investigating the potential of hydrogen fuel cells to replace fossil fuels in specific Brazilian maritime trade routes.

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