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Low-carbon hydrogen production under Brazilian law 14.948/2024

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Abstract. Hydrogen is an element with great energy potential and is emerging as a clean fuel compared to other alternative energy sources. However, its production methods can have high greenhouse gas emissions, making it necessary to apply low-emission production methodologies, resulting in what is known as low-carbon hydrogen. This paper presents methods currently used on a large scale to produce this fuel, as presented in *The Future of Hydrogen* report by the International Energy Agency (2019), and compares the emissions data from these methods with the limits imposed by Brazilian law 14.948/2024, which sets a limit of 7 kilograms of carbon dioxide emitted per kilogram of hydrogen produced. Alternative hydrogen production methodologies are also presented, whether they are improvements to already consolidated processes or new methods under development, through the systematic review.
Keywords: hydrogen, low carbon hydrogen, hydrogen production, systematic review.

Producția de hidrogen cu emisii scăzute de dioxid de carbon în conformitate cu legislația braziliană 14.948/2024

Rezumat. Hidrogenul este un element cu un mare potențial energetic și este în curs de dezvoltare ca un combustibil curat în comparație cu alte surse alternative de energie. Cu toate acestea, metodele sale de producție pot avea emisii ridicate de gaze cu efect de seră, ceea ce face necesară aplicarea metodologiilor de producție cu emisii scăzute, producând ceea ce se numește hidrogen cu emisii scăzute de carbon. Această lucrare prezintă metode utilizate în prezent pe scară largă pentru a produce acest combustibil, așa cum este prezentat în Raportul *Viitorul Hidrogenului* de către International Energy Agency (2019), și compară datele privind emisiile din aceste metode cu limitele impuse de legea braziliană 14.948/2024, care stabilește o limită de 7 kilograme de dioxid de carbon emis pe kilogram de hidrogen produs. Sunt prezentate, de asemenea, metodologii alternative de producție a hidrogenului, indiferent dacă acestea sunt îmbunătățiri ale proceselor deja consolidate sau ale noilor metode în curs de dezvoltare, prin revizuirea sistematică.
Cuvinte-cheie: hidrogen, hidrogen cu emisii reduse de carbon, producția de hidrogen, revizuire sistematică.

1. Introduction

Due to climate change in recent years, several ways of reducing greenhouse gas emissions have been studied, especially in the area of low-emission or zero-carbon renewable fuels, highlighting hydrogen among several alternatives (Table 1).

Silva [20] indicates that hydrogen as a fuel has an energy potential of 2.5 to 3.5 times higher than hydrocarbon-based fuels, in addition to emitting only water vapor as a product of combustion and thermal energy, being considered a clean fuel.

Table 1. Energy densities of fuels at 25 °C

Fuel	Hydrogen	Gasoline	Natural Gas	Methane	Methanol	Ethanol	Kerosene	Coal	Wood
Energy density ($MJ.kg^{-1}$)	141.90	47.27	47.21	55.55	22.69	29.70	46.00	31.38	17.12

Source: Adapted from Ett and Reis [8].

However, International Energy Agency data [14] report that approximately 99% of all global hydrogen production comes from high carbon emission raw materials: 76% from natural gas and 23% from coal. For Gonçalves *et al.* [9] low-carbon hydrogen can use methods that emit these gases, however Carbon Capture, Utilization, and Storage techniques must be applied (CCUS).

The definition of low-carbon hydrogen can be made based on production processes or their desired emissions depending on the legislation used as a reference, being defined in Brazil by law 14.948 of August 2, 2024, which aims to regulate the production of low-carbon hydrogen in Brazil, defining what is low-carbon hydrogen and the maximum values of carbon dioxide equivalent established:

"Art. 4° [...] XII - low-carbon hydrogen: hydrogen fuel or industrial input collected or obtained from various production sources and that has GHG emissions, according to life cycle analysis, with an initial value less than or equal to 7 kg CO_2-eq/kg H_2 (seven kilograms of carbon dioxide equivalent per kilogram of hydrogen produced) [...]." [5].

Low-carbon hydrogen is proposed to be a cleaner fuel than hydrogen produced without a specific limit on greenhouse gas emissions. This characteristic contributes to its use being a short-term solution when compared to the use of other fuels with comparable characteristics [13] or zero-emission hydrogen. However, zero hydrogen has high energy costs as an obstacle to its large-scale production [20].

With the values defined by the Brazilian legislation, it is possible to evaluate which routes used for the production of hydrogen are considered low carbon, with this work proposing to carry out this evaluation, being complemented by a systematic quantitative review of basic nature to present alternative methods for low-carbon hydrogen production.

2. Methodology

As a criterion for the selection of current methods for hydrogen production, the methods presented in chapter 2 of the report *The Future of Hydrogen* by the International Energy Agency [14] were chosen. This report was selected because of the credibility of the agency that produced it, with the objective of presenting it for the G20 meeting in Japan in 2019.

For the selection of alternative methods for low-carbon hydrogen production, a systematic review was conducted in October 2024. We searched for publications of articles in the period from 2019 to 2023 in the Science Direct database, applying a series of criteria for the inclusion of articles to be analyzed.

The keywords ”hydrogen production” AND ”low carbon hydrogen” were used as search criteria and then the following inclusion criteria were applied: the selection of research and review articles, access and files be freely accessible and free of charge. To limit the search for articles that present low carbon hydrogen production, we included the keywords AND ”low carbon hydrogen production” after considering the previous criteria, along with the keywords already added.

The selected articles were analyzed for their titles and abstracts, considering whether their content addressed alternative hydrogen production methodologies to those presented in chapter 2 of the report *The Future of Hydrogen* by the International Energy Agency [14], with a complementary analysis to identify works that only bring case studies of current methodologies, with these works being disregarded. After the selection of articles regarding the approach to methodologies, the works were categorized according to their study objective.

3. Results and discussion

3.1. Methods currently employed in obtaining hydrogen

Chapter 2 of the report *The Future of Hydrogen* [14] presents the methods of hydrogen production, indicating the main sources: natural gas, coal, biomass and water, as described in Table 2:

Table 2. Methods of obtaining hydrogen based on their sources

Source	**Methods of obtaining**
Natural Gas	Steam Methane Reforming (SMR)
	Partial Oxidation (POX)
	Autothermal Reform (ATR)
Coal	Coal gasification
Biomass	Biomass gasification
Water	Electrolysis

Source: Adapted from International Energy Agency [14].

3.2. Emissions

Despite being a fuel that doesn't emit greenhouse gases in its combustion, the production of hydrogen is responsible for emissions during its production. Gonçalves *et al.* [9] present data of these emissions in different production methodologies, as shown in Figure 1:

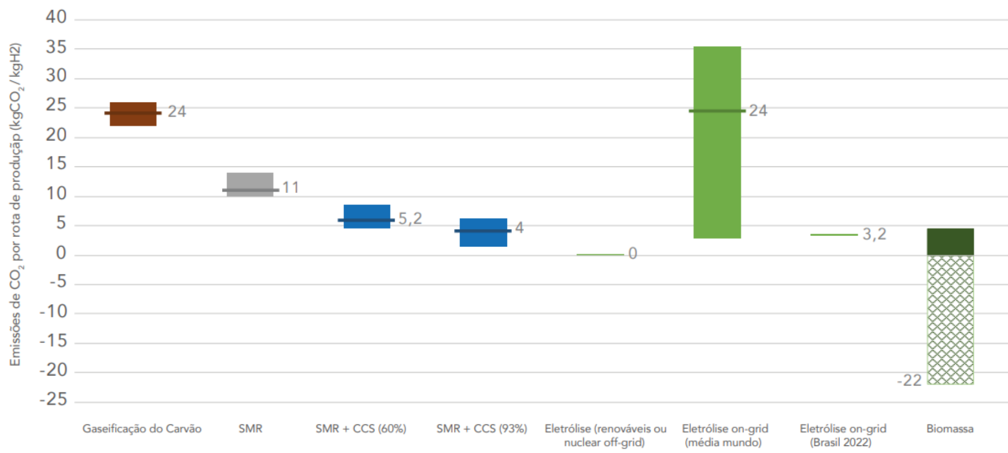

Figure 1. Carbon dioxide equivalent emissions per kilogram of hydrogen produced in each production methodology

Source: Gonçalves *et al.* [9].

The gasification of coal has a high emission, between 22 and 26 kg CO_2-eq/kg H_2, while the values emitted by methane vapor reform vary between 10 and 14 CO_2-eq/kg H_2 according to Gonçalves *et al.* [9] and 10 to 12 CO_2-eq/kg H_2 according to the International Energy Agency [12].

When applying CCUS technologies in the SMR methodology, emissions fall to values between 1.5 and 8 kg CO_2-eq/kg H_2 depending on the capture methodology used, presenting values that comply with Brazilian legislation.

The electrolysis emissions from renewable matrices, nuclear or off-grid (out of the transmission network) tend to be zero, however, nuclear energy generates waste that emits ionizing radiation requiring specific treatment. For electrolysis, whose energy matrix is on-grid (connected to the transmission network), emissions tend to vary depending on the generation source. With the world's energy matrix based on more than 60% non-renewable power generation sources such as natural gas and coal, emissions tend to reach up to 35 kg CO_2-eq/kg H_2 with on-grid electrolysis.

The Brazilian average stands at 3.2 kg CO_2-eq/ kg H_2 of emissions generated by on-grid electrolysis, resulting from the Brazilian energy matrix being composed of more than 80% renewable energy. Making Brazil an ideal country for the investment in electrolytic hydrogen production technologies.

Biomass has a relatively low maximum emission, being below 5 kg CO_2-eq/kg H_2, but it draws attention to its potentially negative emissions, the result of CO_2 consumed by biomass in the field [9]. Autothermal reforming (ATR) and partial oxidation (POX) technologies are not included in the graphs of Gonçalves *et al.* [9], but data from the International Energy Agency [12] report that direct emissions with CCS are less than 3 kg CO_2-eq/kg H_2.

3.3. Alternative methodologies for low-carbon hydrogen production

The results of the systematic review generated a total of 15 articles focusing on production methodologies, which were evaluated and categorized according to their approach:

A - Alternative methodologies for hydrogen production (5 articles)

Articles with the objective of studying hydrogen production methodologies different from those presented as methods employed by industry according to chapter 2 of the report *The Future of Hydrogen* of the International Energy Agency [14].

B - Improvement studies for current methodologies (10 articles)

Articles that address currently used methodologies, but with process improvements aimed at reducing emissions and increasing production efficiency:

Table 3. Articles evaluated in Category A: Alternative hydrogen production methodologies, presented from A1 to A5

No.	Title
A1	Modelling of sorption-enhanced steam reforming (SE-SR) process in fluidised bed reactors for low-carbon hydrogen production: A review (2023)
A2	How sustainable and profitable are large-scale hydrogen production plants from CH_4 and H_2S? (2023)
A3	Methane pyrolysis on sponge iron powder for sustainable hydrogen production (2022)
A4	A critical review on the principles, applications, and challenges of waste-to-hydrogen technologies (2020)
A5	Assessing the prospective environmental performance of hydrogen from high-temperature electrolysis coupled with concentrated solar power (2022)

Source: Prepared by the authors (2024).

Table 4. Articles evaluated in Category B: Improvement studies for current methodologies, presented from B1 to B10

No.	Title	Current Processes Addressed
B1	Reducing the cost of low-carbon hydrogen production via emerging chemical looping process (2022)	SMR/ATR
B2	Optimal design of an MDEA CO_2 capture plant for low-carbon hydrogen production – A rigorous process optimization approach (2021)	SMR
B3	Low-carbon hydrogen via integration of steam methane reforming with molten carbonate fuel cells at low fuel utilization (2021)	SMR
B4	Direct electrification of Rh/Al_2O_3 washcoated SiSiC foams for methane steam reforming: An experimental and modelling study (2023)	SMR

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Table 4 – continued from previous page

No.	Title	Current Processes Addressed
B5	Ternary-phase nanostructure W_3P/WP/W for high-performance pH-universal water/seawater electrolysis (2022)	Electrolysis
B6	Comprehensive process simulation of a biomass-based hydrogen production system through gasification within the BECCS concept in a commercial two-stage fixed bed gasifier (2023)	Biomass
B7	Blue, green, and turquoise pathways for minimizing hydrogen production costs from steam methane reforming with CO_2 capture (2023)	SMR and Electrolysis
B8	Analysis of hydrogen production costs in Steam-Methane Reforming considering integration with electrolysis and CO_2 capture (2022)	SMR and Electrolysis
B9	Carbon-negative hydrogen from biomass using gas switching integrated gasification: Techno-economic assessment (2022)	Electrolysis
B10	A review on bi/polymetallic catalysts for steam methane reforming (2023)	SMR

Source: Prepared by the authors (2024).

In total, 7 studies address the SMR technology with or without association to other technologies, while biomass is addressed in 2 studies and electrolysis, without association to other technologies, in only 1 study.

Even without the association with other technologies, SMR is still responsible for most of the studies aimed at improving processes, which is expected because the Steam Methane Reforming uses natural gas as a source, accounting for 76% of the world's dedicated hydrogen production [14]. Although biomass is not a major raw material in hydrogen production, there are considerable studies for the improvement of this process. These data indicate that the improvement of already established technologies is the best scenario for increasing low-carbon hydrogen production, especially in the short term, requiring only the adaptation of existing processes and plants instead of a project development that can take months or years.

4. Conclusion

We concluded that it was possible to identify alternative methodologies for hydrogen production, as well as the analysis of current methodologies regarding their emissions according to the literature reviewed and compared to the Brazilian law.

The analysis of emissions presented in current production methodologies demonstrates the importance of CCUS technologies to reduce emissions, being determining factors for non-renewable and high-emission sources to fall within the low-emission standards.

It was possible to identify among the literature review studies that there is a greater number of methodologies for the improvement of current processes compared to alternative methodologies considered as current. These values may indicate that modernizing production plants to become less polluting and more efficient is more effective than building new plants with experimental methodologies, especially when seeking short- and medium-term solutions.

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