Implementation and feasibility of green hydrogen in Colombian kitchens: an analysis of innovation and sustainability

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ABSTRACT

This study explores the potential of green hydrogen as a sustainable energy solution in domestic cooking, focusing on Colombia. It employs a systematic literature review following the PRISMA framework, analyzing articles published between 2018 and 2023 to assess the feasibility and challenges of implementing green hydrogen in the culinary sector. The research emphasizes the projected growth in the demand for clean hydrogen, particularly in the industrial sector by 2030 and in new applications by 2050, with an estimated increase from less than 1% currently to about 30% of the total hydrogen demand. It is anticipated that green hydrogen production will dominate the global supply mix by 2050, reflecting a share of between 50% and 65% in various scenarios. The study concludes that while green hydrogen holds great potential for transforming Colombia's energy matrix towards a cleaner, more sustainable future, it faces significant regulatory and technical challenges that require concerted, collaborative action, aligning with the sustainable development goals.

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1. INTRODUCTION

The global transition to sustainable energies, prominently featuring green hydrogen, is vital in combating climate change. This eco-friendly produced compound, emitting no carbon, is a key player in the decarbonization of various sectors, including domestic settings. The kitchen, central to daily life, stands to benefit from green hydrogen, offering a clean alternative to traditional fossil fuels and helping reduce environmental degradation and public health issues [1], [2]. This study delves into integrating green hydrogen in kitchen systems, emphasizing technological advancements, economic challenges, and opportunities for clean, accessible cooking solutions.

Globally, around 2.3 billion people use cooking methods based on polluting fuels, linked to 3.2 million premature deaths annually. Transitioning to clean energies is crucial for mitigating these health and environmental risks [2], [3]. Green hydrogen, with its clean combustion, emerges as a solution, yet faces challenges like production costs, infrastructure, and user acceptance [4].

The importance of green hydrogen in energy transition is evidenced by its increasing demand, estimated to cover 30% of the total by 2030, and expected to rise to 50-65% by 2050 [5]. This surge signifies a significant shift towards cleaner energies, aligning with global CO_2 emission reduction efforts. This global context presents challenges and opportunities for countries like Colombia, where integrating green hydrogen into the national energy matrix is a promising route towards sustainability.

The article critically assesses technological routes and economic strategies for green hydrogen implementation in cooking. It examines recent innovations in hydrogen production through water electrolysis using renewable energy, and advances in hydrogen-compatible appliances. Furthermore, public policies and business models that could facilitate a transition to cleaner, more accessible cooking solutions are considered [6]. This integrated approach aims to fill the literature gap on domestic green hydrogen use and provide a framework for collective action among policymakers, researchers, and industry. This research seeks to catalyze a shift towards more sustainable cooking practices, contributing to sustainable development goals and a cleaner energy future.

The study focuses on evaluating the feasibility and sustainability of green hydrogen use in domestic kitchens in Colombia. Its specific objectives are to analyze current green hydrogen technologies and their applicability in domestic kitchens; assess the economic and accessibility aspects of green hydrogen in Colombian homes; and identify necessary policies and regulations to facilitate green hydrogen adoption in cooking. This approach ensures a focused investigation, addressing key technological, economic, and regulatory aspects for green hydrogen implementation in domestic kitchens.

Colombia stands out as a key reference in the implementation of green hydrogen, a commitment aligned with its progressive transition towards renewable energies and the reduction of its dependence on fossil fuels. In this process of energy transformation, the country has established a national plan aiming to increase its non-conventional renewable energy capacity from 1% to 12% of its energy matrix by 2030, according to reports from Mackenzie [7]. This effort is complemented by the vision of the current administration, which prioritizes the energy transition, emphasizing transitional justice and the adoption of sustainable technologies [8].

Colombia's installed electric generation capacity of 17.771 MW is noted for its dependence on hydroelectric power (68%), although the country has significant potential in solar and wind energies, as indicated by the U.S. Department of Commerce [9]. Colombia has made progress in conducting renewable energy auctions and has awarded wind and solar energy projects, contributing to its goal of generating 2.5 GW from sources such as solar, wind, and biomass. In addition, favorable regulatory frameworks have been established for investment in unconventional energy sources, including green and blue hydrogen.

This context in Colombia is key for understanding how green hydrogen implementation and adoption can tackle the country's specific energy challenges and contribute to global sustainability goals. Research in Colombia may provide valuable insights for other developing countries seeking to diversify energy sources and reduce their carbon footprint. Preservation of tangible and intangible cultural heritage, as shown in various studies, includes a feasibility study on renewable-energy-based hydrogen in off-grid domestic energy systems in Italy [10]. This emphasizes the importance of hydrogen storage tank size and performance.

Furthermore, the integration of artificial intelligence (AI) in the energy transition has been identified as a key factor in promoting the use of renewable energies. The development of AI software can facilitate the transition towards cleaner energies by enhancing performance in innovation and environmental monitoring [11]. This approach is particularly relevant for Colombia, where the combination of AI and renewable energies could accelerate the adoption of green hydrogen. AI, through its advanced algorithms, can analyze energy consumption patterns and dynamically adjust the production and distribution of hydrogen. This level of optimized management is crucial for the integration of intermittent renewable energies like green hydrogen into the domestic environment, allowing not only for greater energy efficiency but also for improved sustainability. The implementation of AI systems in hydrogen production can lead to a significant reduction in waste and an improvement in the economic and environmental viability of hydrogen kitchens [12].

Research on the generation of green hydrogen in Colombia highlights the use of renewable energies such as photovoltaic solar, hydroelectric, wind, and biomass, identifying optimal regions for the development of green hydrogen projects and recommending hydroelectricity as a short-term solution and solar energy for the long term [13]. In a complementary approach, the operability of a green hydrogen plant powered by photovoltaic solar energy and connected to the grid is examined, demonstrating its efficiency and profitability in Colombia [14]. Moreover, green hydrogen is addressed comprehensively, analyzing its production from renewable sources in various countries, including Colombia. The study emphasizes the significant environmental benefits of green hydrogen and its viability as a substitute for fossil fuels, underscoring its applicability in the Colombian energy context [15]. The study's guiding question is how technological innovations and economic policies can overcome barriers to adopting green hydrogen in domestic cooking. The hypothesis is that a combination of advances in appliance technology and economic incentives can make green hydrogen a viable, preferred energy source for cooking, reducing the carbon footprint and improving global public health.

2. METHOD

The methodology of this study adopts a systematic literature review (SLR) approach, based on the PRISMA framework [16], [17]. This process consists of four key phases: defining the review protocol, developing a search strategy, executing the review, and analyzing the results. Each phase is crucial to ensure the integrity and relevance of the included studies, allowing for a thorough and comprehensive synthesis of the existing literature.

Phase I - Defining the protocol and search strategy: digital libraries such as Science Direct, IEEE Xplorer, Scopus, Elsevier, and Springer were explored. Inclusion criteria included articles from 2018 to 2023 in English, related to the research question, and electronically available. Exclusion criteria encompassed opinion pieces, conference posters, short and unpublished works, and those not applying green hydrogen [18].

Inclusion criteria:

- Research articles published between 2018 and 2023.
- Studies aligned with the search string: ("green hydrogen" OR "renewable hydrogen energy") AND (kitchen OR cooking) AND ("low cost" OR affordable OR economical) AND (innovation OR technology OR implementation).
- Publications in the English language.
- Articles available in recognized academic databases.
- Works that offer technological, economic, or policy perspectives relevant to green hydrogen in cooking contexts.

Exclusion criteria:

- Publications outside the time frame of 2018 to 2023.
- Articles not directly related to the terms in the search string.
- Documents in languages other than English.
- Grey literature such as expert opinions, conference posters, abstracts, and unpublished works.
- Studies that do not address research methodologies applicable to the field of green hydrogen in cooking.

Phase II - Expansion through snowballing: In the second phase of the study, the snowballing technique was implemented, consisting of a meticulous review of the bibliographic references of the 13 previously selected articles. This strategy allowed for the identification of additional studies that had not been captured in the initial search, expanding the set of relevant articles by 20%. As a result, a total of 15 articles were obtained that potentially contributed value to the study on green hydrogen in cooking [19].

Phase III - Analysis of abstracts: The third phase of the process consisted of a detailed evaluation of the abstracts of the 15 articles. Rigorous relevance criteria related to the research question were applied, with the goal of determining their direct relevance to the topic. This thorough review led to the conclusion that approximately 80% of the articles, that is, 12 of them, were suitable for moving to the next level of analysis [20].

Phase IV - Full-text selection: The last phase of the review process focused on the exhaustive analysis of the full text of the 12 selected articles. At this stage, an even stricter selection criterion was employed, based on the detailed relevance and specific contribution of each article to the topic of green hydrogen in cooking applications. This meticulous process resulted in the final selection of 6 fundamental articles, each providing valuable insights and significant advancements in the field of study [21].

Figure 1 presents the detailed process of the systematic literature review carried out for this study on green hydrogen in cooking. Each phase of the process is clearly delineated and differentiated by colors for easy understanding. This visual scheme helps to illustrate how the articles were selected and filtered throughout the different stages of the review.

As seen in Figure 1, the process of systematic literature review is a structured and rigorous method, essential for ensuring the quality and relevance of the research. Through this process, it was possible to identify and select the most pertinent and significant studies on green hydrogen in the context of cooking. This methodical approach ensures that the conclusions and recommendations are well-founded on the most current and relevant evidence available.

3. RESULTS AND DISCUSSION

The co-occurrence and bibliometric density analysis depicted in Figures 2 and 3 [22]–[24] provides a visualization of the research landscape in the field of green hydrogen applied to cooking, highlighting current trends and areas of emerging interest. This study investigated the specific effects of green hydrogen on cooking technologies. While previous research has examined the impact of renewable energies on cooking applications, there is a gap in knowledge specific to how green hydrogen can influence the efficiency and sustainability of these technologies. Our approach aims to fill this gap, exploring not only the viability of green hydrogen but also its potential to revolutionize domestic cooking practices.

Figure 2 shows how terms like "green hydrogen," "sustainability," and "renewable energies" are strongly interconnected, suggesting a research focus centered on the ecological production and application of hydrogen in cooking systems. On the other hand, Figure 3 highlights areas of greater research density, indicating intensive fields of study and potential knowledge gaps. These bibliometric maps indicate robust interdisciplinarity and a convergence on themes of hydrogen production, environmental implications, and technological developments. However, they also point out the need for further research in less explored areas such as the integration of policies and business models for the adoption of green hydrogen technologies in domestic cooking. These findings direct future research towards critical areas that require attention for the transition towards a cleaner and more sustainable kitchen.

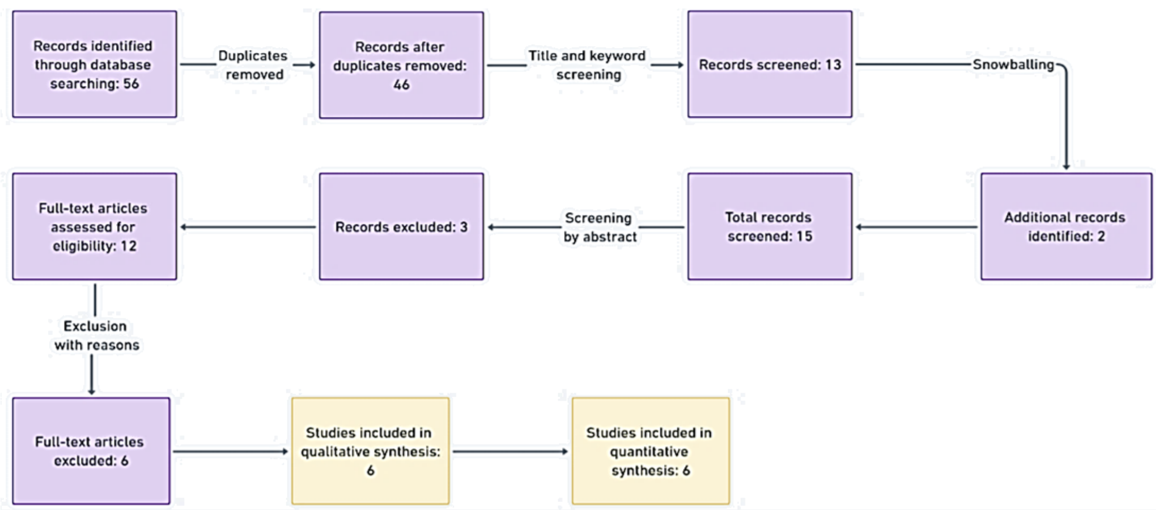


Figure 1. Systematic literature review process for the study of green hydrogen in cooking

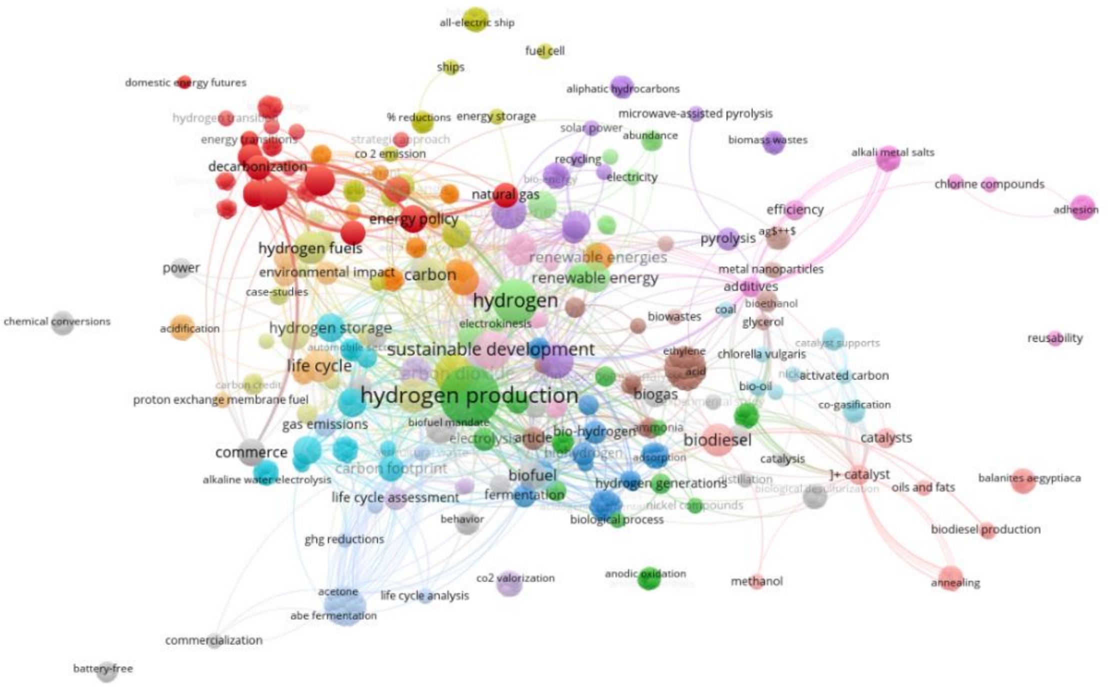


Figure 2. Co-occurrence map of key terms

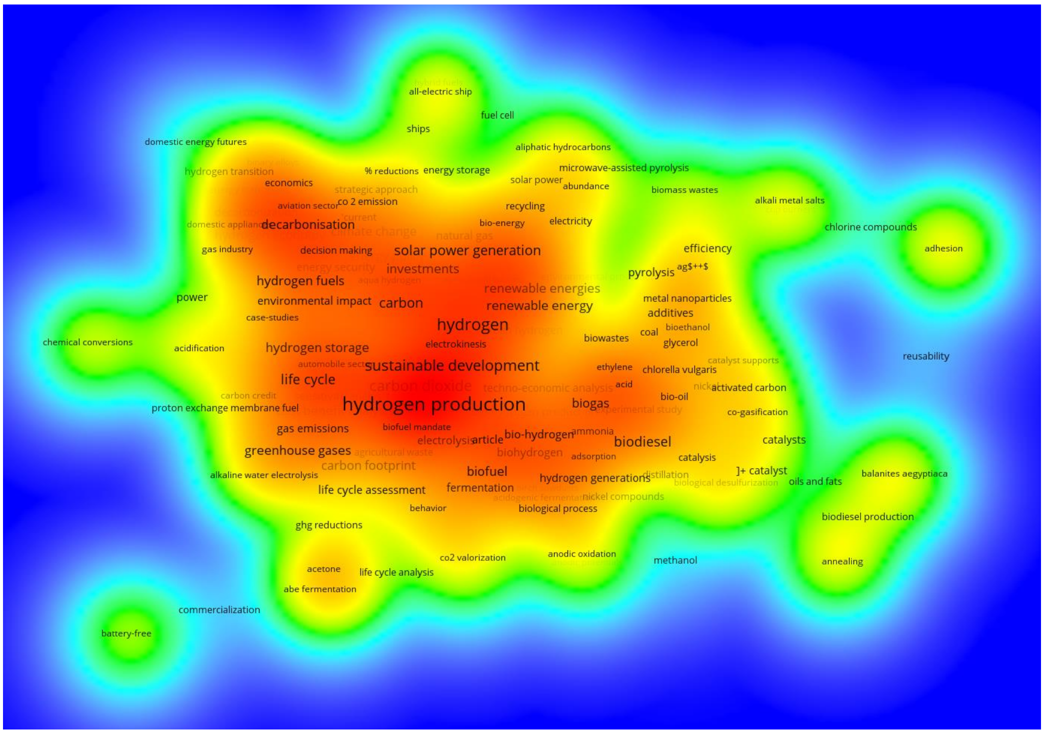


Figure 3. Bibliometric density map

Figure 4 illustrates the distribution and relationship of the themes extracted from the initial 56 articles. This thematic map categorizes key terms into 'Niche Themes', 'Motor Themes', and 'Basic Themes'. Based on their degree of development and central relevance in the corpus of the literature [25], [26].

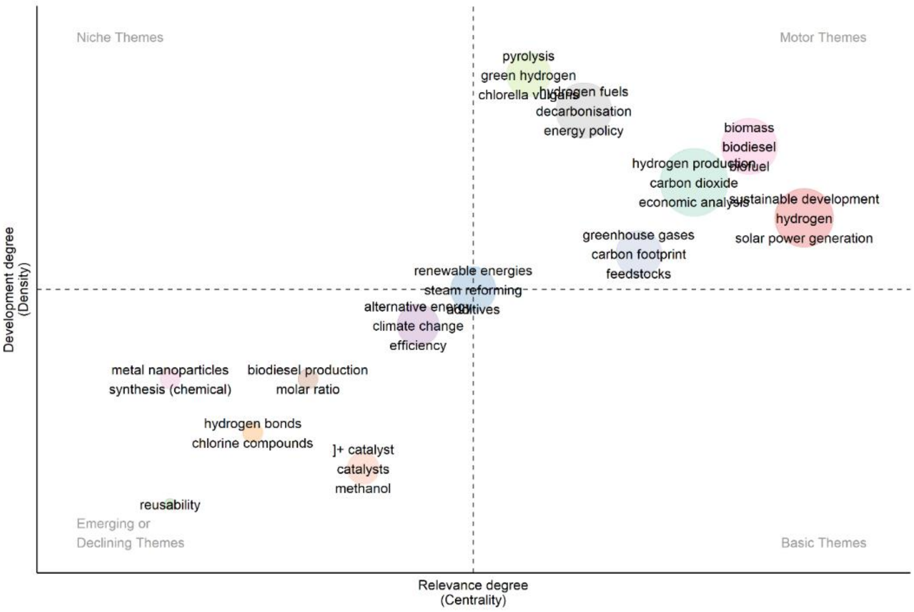


Figure 4. Thematic map of the literature review

In the 'Niche Themes', we find terms such as "metal nanoparticles" and "biodiesel production," which, although important, show an incipient or declining degree of development in current literature [27].

In contrast, the 'Motor Themes', located in the upper right corner, include topics like "biomass," "sustainable development," and "hydrogen production," which are central and well-developed, indicating maturity in research and significant influence on related studies [28]. The 'Basic Themes', on the lower horizontal axis, represent fundamental themes in the literature but with a lower degree of development compared to the 'Motor Themes'. Here, terms like "renewable energies" and "climate change" are included, which are widely recognized areas but still require development in the specific context of green hydrogen in cooking [26].

The density and centrality of the themes in this map suggest that the production of green hydrogen and its application in clean cooking systems is a well-established field of study, but with room for innovation and development in more niche areas. It is evident that research is evolving towards the integration of sustainable solutions into everyday life, with a particular emphasis on efficiency and energy policy [25]. This thematic analysis reinforces the need to continue exploring interdisciplinary and technological solutions that address environmental and sustainability challenges.

The global transition to cleaner and more sustainable energies is a critical issue today, with green hydrogen being a key component in this shift. Table 1 (in Appendix), derived from the systematic literature review of this work, presents a selection of fundamental studies in this field. This table provides a detailed comparison of research focused on the production, adoption, and acceptance of hydrogen, outlining strategies for its effective integration into society. This analysis offers a comprehensive and critical view of the potential paths towards a sustainable energy future powered by hydrogen.

This section incorporates a detailed analysis of green hydrogen technologies applied to kitchens, highlighting advances in production and adapted appliances. Specific data on efficiency, costs, and feasibility are discussed, showing how green hydrogen can be a viable and sustainable solution for modern kitchens. Additionally, the implications of these findings in overcoming technological and economic barriers are examined, emphasizing the relevance of the study in the context of sustainable development goals and the transition to a cleaner energy future.

The documents analyzed demonstrate a consensus on the critical importance of green hydrogen in the future energy matrix. However, Table 1 (in Appendix) reveals significant challenges in public knowledge and acceptance, underscoring the need for informed policies and consumer-oriented market strategies. It is crucial to address generational and regional gaps in hydrogen perception to facilitate an inclusive and effective energy transition. Future research must be cross-sectional and multidisciplinary, integrating technological, economic, and social perspectives to ensure a harmonious adoption of green hydrogen. The table emphasizes the relevance of a holistic and adaptive approach to overcome socioeconomic and technical obstacles, aligning innovation with public acceptance and long-term viability.

Hydrogen production can be carried out through various processes. Thermochemical processes use heat and chemical reactions to release hydrogen from organic materials such as fossil fuels and biomass, or from materials like water. Water (H_2O) can also be split into hydrogen (H_2) and oxygen (O_2) through electrolysis or solar energy. Additionally, microorganisms like bacteria and algae can produce hydrogen through biological processes. These methods offer diverse pathways for hydrogen production, each with its own advantages and challenges. In line with the optimization of technological processes, a key factor in the efficiency of the hydrogen system is the integration of automation and AI. These technologies allow for precise control in hydrogen production, reducing the incidence of human errors and enhancing operational efficacy. The implementation of automated systems and AI solutions can lead to smarter and more reactive energy management, essential for maximizing both the safety and profitability of hydrogen kitchens [29].

According to the "Global Hydrogen Review 2023" from the International Energy Agency (IEA), global hydrogen usage reached a historic high of 95 Mt in 2022, representing an increase of nearly 3% compared to the previous year. However, this growth does not reflect a success of policies to expand hydrogen use, but is more linked to general global energy trends. The demand remains concentrated in the industry and refining sectors, with less than 0.1% coming from new applications in heavy industry, transport, or power generation [30]. Moreover, the report highlights that the demand for low-emission hydrogen barely represents 0.7% of the total hydrogen demand, implying that hydrogen production and use in 2022 were linked to more than 900 Mt of CO_2 emissions. Despite recent government efforts to promote the production of low-emission hydrogen, measures to stimulate its use are still not sufficient to meet climate ambitions [30]. The hydrogen council in its "Hydrogen Insights 2023" reports that the momentum of hydrogen continues to accelerate with over 1,000 projects announced globally, requiring an investment of 320 billion dollars; however, investment decisions are lagging, with only 10% of the investment volumes having passed the final investment decision (FID) phase. This report represents a collaborative effort to share an objective, holistic, and quantitative perspective on the state of the global hydrogen ecosystem [31].

In this context of evolution and challenges in the hydrogen sector, a crucial aspect is the transformative role of AI and digitalization. AI is becoming an essential tool for achieving decarbonization and providing modern, efficient, and affordable energy services. Through its ability to optimize electrical grids and support the integration of renewable energies, AI contributes significantly to energy sustainability.

This technology not only improves energy consumption management in buildings and homes but is also key to achieving a future with net-zero emissions, which has important implications for the development and implementation of green hydrogen cooking solutions [32].

These data suggest that, although green hydrogen shows promising growth, it still faces significant challenges in terms of adoption and investment. In the context of green cooking, these findings underline the importance of addressing both the production and demand for hydrogen, ensuring that policies and strategies promote its use in domestic applications such as cooking. Furthermore, it is crucial that adoption strategies consider consumer perception and acceptance to ensure an effective transition towards more sustainable cooking practices. A notable case study in the domestic application of green hydrogen is observed in an international project that has developed a system for the production and storage of green hydrogen using transparent photovoltaic cells (TPV) and photoelectrochemical cells (TPEC). This system, which can be integrated into buildings, demonstrates the viability of green hydrogen in domestic environments. Through its ability to supply uninterrupted energy, this innovative approach underscores the potential of green hydrogen to transform cooking practices towards more sustainable and efficient methods [33]. The implementation of kitchens using green hydrogen as fuel involves an integrated approach that considers both hydrogen production and its final use in a domestic environment. The following Table 2 presents the classification of different types of hydrogen: blue, gray, brown, black, and green.

Table 2. Types of hydrogen and their environmental impacts

Designation	Technology	Description	Source	Products	Cost ($ kg/H_2)	CO_2 emissions
Brown hydrogen	Gasification	Produced through coal gasification, associated with high CO_2 emissions [34].	Lignite (black coal)	$H_2 + CO_2$	1.2 – 2.1	High
Black hydrogen	Gasification	Produced through coal gasi-fication, associated with high CO_2 emissions [34].	Bituminous coal	$H_2 + CO_2$	1.2 – 2.1	High
Grey hydrogen	Reforming	Derived from natural gas reforming, representing the majority of current production, with significant CO_2 emissions [35].	Natural gas	$H_2 + CO_2$ (released)	1 – 2.1	Medium
Blue hydrogen	Reforming+ carbon capture	Similar to grey hydrogen but with car-bon capture, reducing CO_2 emissions, with a slightly higher cost [36].	Natural gas	$H_2 + CO_2$ (captured 85-95%)	1.5 – 2.9	Low
Green hydrogen	Water splitting (electrolysis)	Produced through water electrolysis with renewable energy, emits no CO_2, but its cost is higher compared to fossil fuel-based ones [37]	Water	$H_2 + O_2$	3.6 – 5.8	Minimum

Colombia, with its growing commitment to sustainability and reducing its carbon footprint, can significantly benefit from the adoption of green hydrogen technologies in its energy and domestic sectors. Transitioning to kitchens using green hydrogen could be an innovative step in this direction. Green hydrogen offers an opportunity for Colombia to move towards a cleaner energy future by leveraging its potential in renewable energies such as solar and wind, which are crucial for the production of green hydrogen through electrolysis. By integrating these renewable energy sources, Colombia could reduce its dependence on fossil fuels and lower greenhouse gas emissions, aligning with its environmental goals and international commitments like those agreed upon in the Paris agreement [38], [39].

Furthermore, the implementation of green hydrogen kitchens in Colombia could stimulate the local and regional economy through the creation of new jobs in manufacturing, installation, and maintenance of the necessary infrastructure and compatible appliances. This development could encourage innovation and position the country as a leader in the adoption of clean technologies in latin America. Government efforts to promote the adoption of green hydrogen, such as tax incentives or subsidies, would be fundamental in facilitating this transition [40], [41].

Green hydrogen emerges as a potential solution for the energy transition and the decarbonization of key industrial sectors such as the chemical, steel, and cement industries, as well as the aviation and maritime transport sectors [42]. In the Colombian context, the momentum of green hydrogen can be particularly beneficial, considering the country's abundant renewable energy sources and the growing ecological awareness at both the civil and governmental levels [43]. In the search for sustainable energy solutions, green hydrogen has positioned itself as a promising alternative, especially in the field of domestic cooking. Green hydrogen cooking technologies offer a path towards cleaner and more ecological cooking, aligning with global objectives of reducing carbon emissions and promoting renewable energies [44]. These technologies are primarily divided into two categories as shown in Figure 5, direct combustion kitchens and catalytic combustion kitchens. Both present unique characteristics in terms of design, operation, and safety, making them suitable for different applications and environments [45].

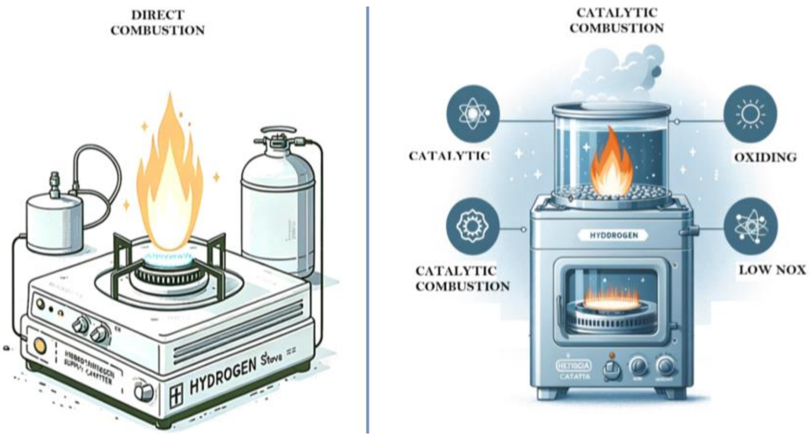


Figure 5. Hydrogen-based kitchen technologies: direct and catalytic combustion

Figure 5 displays two schematic diagrams representing the two main hydrogen-based kitchen technologies:

- Direct hydrogen combustion kitchen: this diagram shows a simple burner connected to a container representing the hydrogen supply. This type of kitchen generates a flame from hydrogen and requires appropriate safety systems, such as flame arresters, to prevent accidents. Direct combustion is effective but must be handled carefully due to the high temperatures of the flame [46].
- Catalytic hydrogen combustion kitchen: the second diagram depicts a kitchen utilizing catalytic combustion. Instead of an open flame, this design uses a catalytic element that allows for low-temperature oxidation, virtually flameless. This method is safer and significantly reduces the risk of burns or fires. Additionally, catalytic combustion kitchens are efficient and emit less NOx, contributing to reduced air pollution [47].

Both designs reflect the potential of green hydrogen to transform the way we cook, offering cleaner and more sustainable alternatives compared to traditional fuels. Figure 6, as a contribution of this work, provides a detailed view of the process of developing these technologies, covering everything from process inputs to key performance indicators (KPIs). This comprehensive approach is crucial for understanding the complexity and challenges associated with the design and implementation of green hydrogen-based kitchens, a topic that has been explored in recent studies [48]–[50].

The diagram in Figure 6 begins with "Process Inputs," highlighting the importance of various hydrogen sources, which are fundamental in determining the overall sustainability and efficiency of the system. The "Initiation" phase marks the start of the design and planning process. Following this, the "Burner Design" phase is crucial, as it needs to be adapted to the specific type of hydrogen used. The "Kitchen Type Decision" stage involves choosing between a "Direct Combustion Kitchen" and a "Catalytic Kitchen". This decision significantly influences the subsequent "Combustion System Design", tailored to the specific type of kitchen. The "Safety System Design" is a critical phase, focused on ensuring the safe use of hydrogen in domestic environments. The "Evaluation and Testing" phase involves rigorous testing of the designs and systems to ensure their safety and efficacy, a process extensively discussed in the literature. The process culminates in the "Completion" phase, leading to "Process Outputs," where the final products of the design process materialize, such as the "Complete Burner Design" and the "Combustion System". Additionally, the diagram considers "Waste/Byproducts" generated, "Associated Equipment/Services" used at each stage, and "Key Performance Indicators (KPIs)", such as design efficiency, burner safety, and combustion system efficacy. We have found that green hydrogen, when integrated into cooking systems, correlates with increased sustainability and energy efficiency. This result underscores the importance of developing and implementing cooking technologies adapted to green hydrogen.

Furthermore, the transition to using green hydrogen in Colombia, specifically in cooking applications, can significantly contribute to the country's sustainable development goals (SDGs). For example, SDG 7 aims to ensure access to affordable, reliable, sustainable, and modern energy. Implementing green hydrogen technology in kitchens would help reduce dependency on fossil fuels and promote the use of clean and renewable energies [46]. Additionally, aligning with SDG 9, which emphasizes innovation and sustainable infrastructure, developing green hydrogen kitchens could foster technological innovation and stimulate the economy through job creation in emerging sectors. On the other hand, SDG 13, which urges urgent action to combat climate change and its impacts, would be supported by the reduction of CO_2 emissions that green hydrogen adoption implies [47].

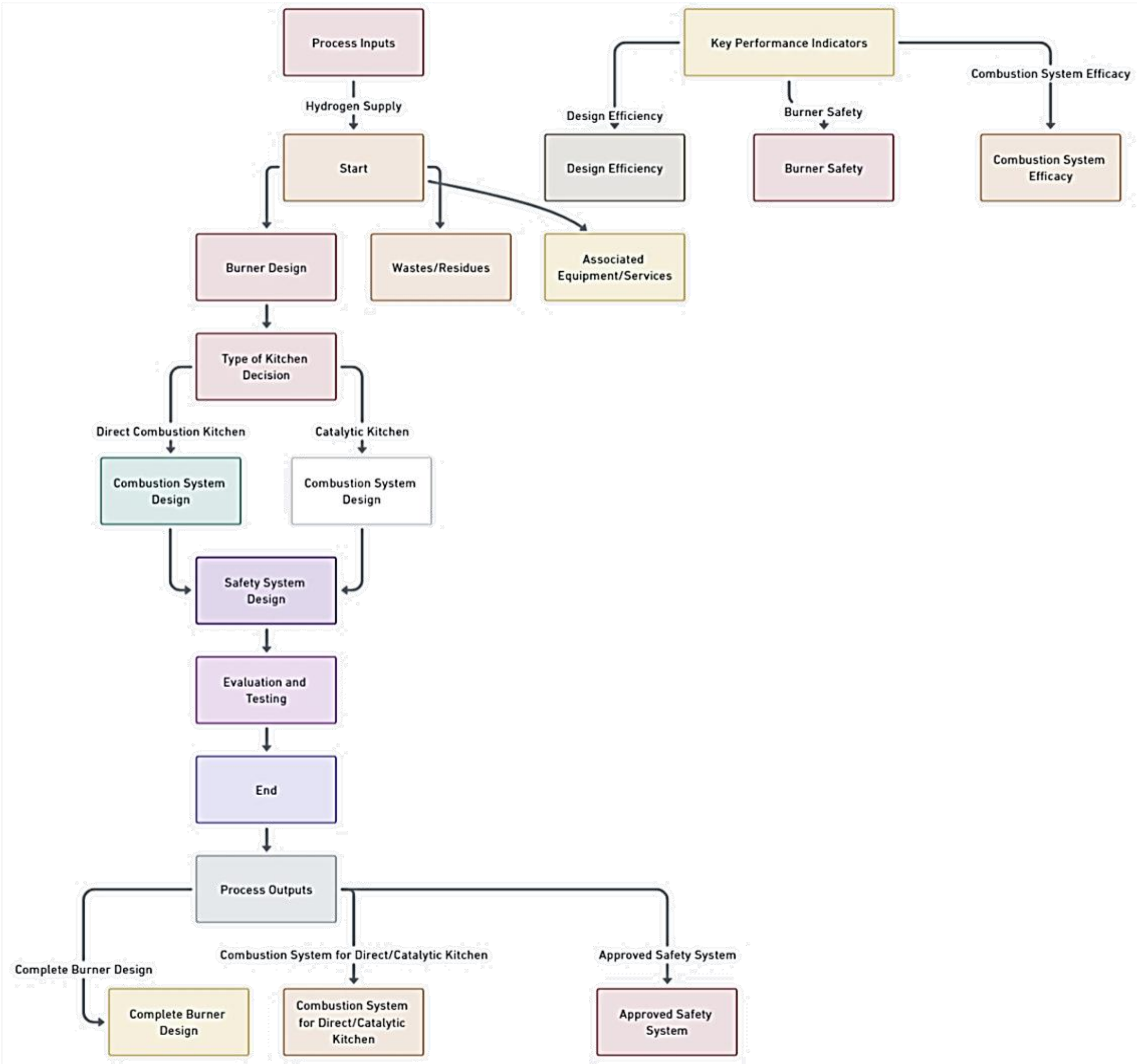


Figure 6. Green hydrogen-based kitchen technology development process with KPIs

To address the specific challenges Colombia faces in implementing green hydrogen technology, several aspects highlighted in the consulted sources must be considered. One of the main challenges is related to regulation and existing legal barriers. In Colombia, the difficulties in obtaining environmental licenses and the need to establish standards for low-emission hydrogen, as well as regulatory gaps in pipeline transportation, are highlighted. The importance of incentives for technological adaptation and infrastructure, as well as existing tax incentives for related projects, are also mentioned [51].

Although Colombia has ambitious goals to become a significant producer and exporter of green hydrogen by 2030, it faces several challenges to achieve these objectives. Colombia's plan includes installing between 1,000 and 3,000 megawatts of electrolysis capacity, which would require an addition of 4,000 megawatts of unconventional renewable energy sources. Currently, the country only has 360 megawatts of solar and wind energy. Additionally, delays and difficulties with prior consultations, environmental licensing, and administrative procedures represent obstacles for the timely completion of 80 ongoing renewable energy projects. The lack of adequate port infrastructure is also mentioned as an obstacle to Colombia's green hydrogen ambitions [52].

Successful implementation of green hydrogen in Colombia demands a collaborative and meticulously regulated approach. Given the identified challenges, it is imperative to design solutions tailored to the Colombian context. This involves boosting investment in research and development and building a robust regulatory framework that facilitates a smooth transition to this sustainable energy. Additionally, for the effective implementation of green hydrogen-based kitchens, a holistic strategy is required. This should encompass the development of specific infrastructure, the necessary technical training for the operation and maintenance of these innovative systems, and a solid regulatory and public policy base that incentivizes the adoption of this technology. The synergy between the private sector, academia, and government is vital to cultivate the necessary skills and consolidate a robust domestic market for green hydrogen [53].

Our study highlights the viability and environmental benefits of green hydrogen in kitchens, marking it as a crucial component for a sustainable energy transition. While we focus on Colombia, highlighting its potential for adoption and associated benefits, we recognize the need for further research to validate these findings on a broader scale and to understand consumer acceptance. The evidence of the resilience and viability of green hydrogen in domestic applications opens new avenues for research. It is crucial to explore how the integration of advanced technologies, such as artificial intelligence systems, can further optimize the production and utilization of green hydrogen in domestic environments. These efforts can address current limitations and expand the potential application of green hydrogen, significantly contributing to our goals of sustainability and energy efficiency.

3.1. Analysis of hydrogen policies in Colombia and their relevance for domestic implementation

Within the framework of Colombia's energy development, the hydrogen roadmap, set for the period 2021-2030, plays a crucial role, focusing on the development of green and blue hydrogen as essential pillars in the country's energy transition. This approach is aimed at the decarbonization of various economic sectors, with an objective to install between 1-3 GW of electrolyzer capacity for green hydrogen production, utilizing renewable sources such as wind and solar energy. Concurrently, blue hydrogen, produced from fossil sources with carbon capture technologies, is also integrated into this strategy, with a production goal of 50 kt, seeking a balance between both technologies [54], [55]. The infographic in Figure 7 provides a detailed and structured visualization of Colombia's hydrogen roadmap [55], displayed on a timeline that distinguishes two key stages in the development of low-carbon hydrogen in the country.

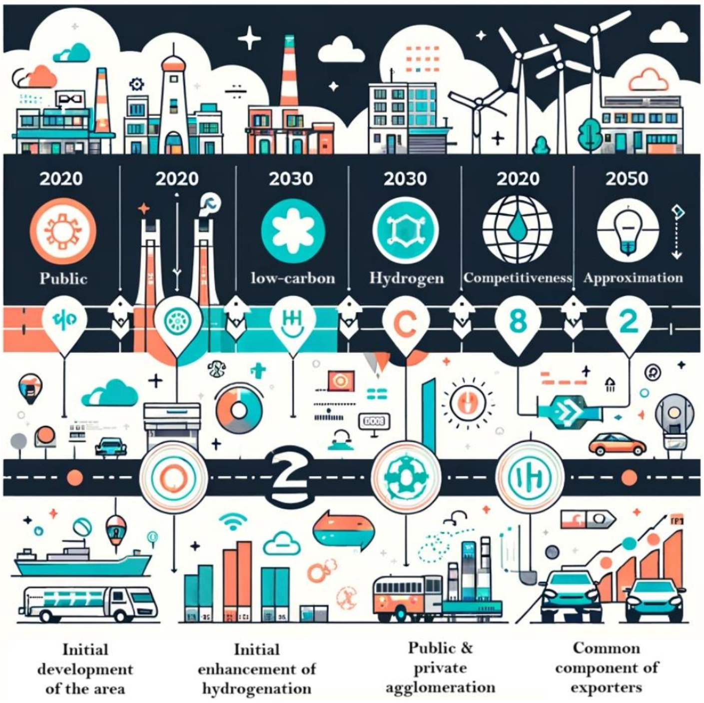
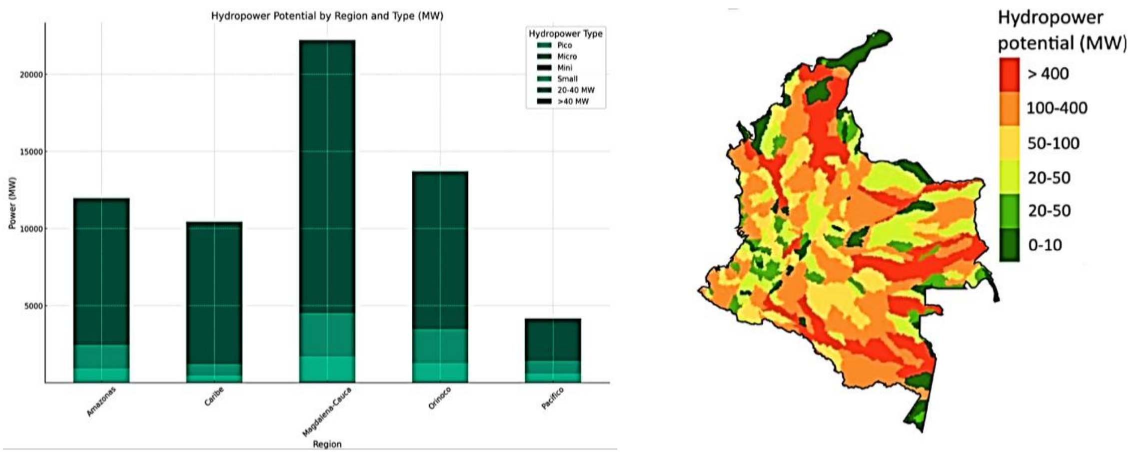


Figure 7. Hydrogen roadmap infographic for Colombia (2020-2050)

The first stage (2020-2030) emphasizes the initial development of the hydrogen market, marked by intensive collaboration between public and private sectors. This crucial period is characterized by the construction of key infrastructure, investments in advanced technology, and the first commercial applications of hydrogen, illustrating the importance of intersectoral synergy and technological innovation in establishing an emerging hydrogen market. Subsequently, the second stage (2030-2050) focuses on the consolidation and expansion of the market, with hydrogen gaining competitiveness in a variety of applications. An increase in demand at both national and international levels is anticipated, heralding a period of innovation and extensive application of hydrogen in various sectors.

In this regard, various studies have highlighted the importance of innovation and safety in implementing green and blue hydrogen technologies. Analyze the transition to a decarbonized future in regions with intense lignite mining, using green hydrogen, an approach relevant to Colombia in its implementation of technologies for the production and utilization of green hydrogen in various sectors [56]. Investigates green and blue hydrogen in hard-to-decarbonize industrial sectors, offering perspectives for industrial decarbonization with hydrogen [57]. Explore the possibility of generating green energy at oil and gas platform locations in Australia, offering ideas applicable to Colombia in its quest for sustainable solutions for hydrogen production [58]. Discuss the energy transition towards hydrogen in the context of chemical engineering, emphasizing the importance of hydrogen and safety challenges [59]. A comprehensive study conducted in Colombia identified a hydroelectric generation potential of 56 GW, primarily in large power plants, which represent 76.76% of the total and have a capacity of over 40 MW. The geographical distribution and specific regional concentration of hydroelectric potential are comprehensively detailed in Figure 8. Figure 8(a) displays the hydroelectric potential by region and type in megawatts (MW), providing a quantitative assessment of the resource, while Figure 8(b) illustrates the distribution of hydroelectric potential across Colombian regions, measured in MW per kilometer of horizontal conduit. This visual representation emphasizes the intensity and geographical spread of the potential [55], [60].



(a) (b)

Figure 8. Overview of hydroelectric potential analysis in Colombia, with (a) showing the hydroelectric potential by region and type in MW, and (b) illustrating the distribution of hydroelectric potential across regions in Colombia, measured in MW per kilometer of horizontal conduit

Colombia is at a turning point in its energy transition, defined by an ambitious plan (2021-2030) aimed at the development of green and blue hydrogen. This approach, driven by the Ministry of Mines and Energy [61], seeks to reduce dependence on fossil fuels and foster local and national economies through a just transition to renewable sources. With special focus on green hydrogen, the initiative aims for a 51% reduction in greenhouse gas emissions by 2030, compared to 2010 levels, and considers the implementation of an emissions trading system and a carbon tax [62].

The energy transition law 2099 of 2021 establishes a fiscal framework to encourage investments in unconventional renewable energies, including tax benefits for green hydrogen in accordance with ,law 1715 of 2014. This legislation covers both blue and green hydrogen, highlighting its role in various industries. The country's roadmap sets specific targets, such as the installation of 1-3 GW of capacity in electrolyzers and the production of 50 kt of hydrogen using fossil sources, but with carbon capture. Additionally, green ammonia is identified as an opportunity in the agricultural sector [55], [63].

In terms of research, Colombia's strategy on green and blue hydrogen represents a significant case study for analyzing the implementation and impact of energy policies in a developing country. It is crucial to explore the influence of these policies on the adoption of green hydrogen in the residential sector, a field with potential for innovation and energy sustainability. A detailed analysis of these policies could reveal challenges and opportunities for the implementation of green hydrogen in domestic applications, contributing to global knowledge on energy transitions in various contexts.

3.2. Economic viability of green hydrogen in kitchens in Colombia

While we have explored various aspects of green hydrogen in the context of sustainable kitchens, a critical assessment of its economic viability is fundamental to understanding its potential in Colombia. Table 3 summarizes the viability of green hydrogen in kitchens in Colombia from various perspectives. The following aspects have been evaluated considering the current literature and their relevance to the Colombian context.

Table 3. Analysis of green hydrogen viability in kitchens in Colombia: key aspects and considerations

Aspect evaluated	Detailed description	Implications for Colombia
Cost of green hydrogen production	The cost of green hydrogen production is directly related to the price of renewable electricity. Studies, such as the one conducted by the authors listed in reference [64], demonstrate that in countries with high renewable energy potential, production costs can become competitive.	Colombia, with its potential in renewable energies like solar and wind, could achieve green hydrogen production costs comparable to those of countries like Morocco and Saudi Arabia, making it feasible for use in kitchens.
Infrastructure and technology for green hydrogen	The effective implementation of green hydrogen requires suitable infrastructure and compatible technologies, as highlighted in the study referenced in [65]. This includes everything from production to end-use in appliances.	For Colombia, this would entail investments in the development of hydrogen-compatible cooking technologies and the necessary infrastructure for its safe distribution and storage.
Potential of renewable energies and hydrogen production	The study by ArcGIS [66] emphasizes the importance of identifying regions with high potential for green hydrogen production, considering factors such as the availability of renewable resources and existing infrastructure.	In Colombia, areas with high solar irradiation or strong wind currents could be identified as ideal locations to establish green hydrogen production plants, thereby reducing costs and increasing accessibility.
Profitability and risks for green hydrogen investors	Evaluating profitability and risks from an investor's perspective, as analyzed in the study referenced in [67], is crucial for attracting investments in new technologies.	For green hydrogen to be an attractive option in Colombia, a stable regulatory framework and incentive policies are required to minimize risks and maximize returns on investments in this technology.

The economic viability of green hydrogen is boosted by technological innovations in production, with expectations of a cost reduction by half by 2030, according to Wood Mackenzie. This decrease in prices, influenced by improvements in the efficiency of proton exchange membrane (PEM) electrolyzers, promises to drive the adoption of green hydrogen in emerging markets, including Colombia. In particular, the favorable conditions for renewable energies, such as solar and wind, in Colombia would allow for competitive energy costs in hydrogen production [68], [69].

The viability of green hydrogen in residential applications benefits from a convergence of factors in Colombia: a rich potential in renewable energies, advances in production, and suitable infrastructure. These elements, along with a stable regulatory framework and incentive policies, are fundamental for attracting investments and ensuring profitability in the residential sector. The future of green hydrogen in Colombian households depends on a comprehensive evaluation of the influence of policies and technological advancements in its adoption. It is crucial to explore strategies to optimize infrastructure and technology, as well as understand the economic and environmental implications of this energy transition.

3.3. Environmental impact of green hydrogen and its application in kitchens in Colombia

Recognizing the importance of a comprehensive analysis of the environmental impact of green hydrogen, Table 4 synthesizes findings from relevant international studies. Although no specific research for Colombia was identified, these studies provide an overview that allows us to infer implications applicable to the Colombian context, especially in terms of long-term effects and comparisons with other renewable energies. Moreover, it is important to consider Colombia's commitment to the energy transition. The Colombian government has announced plans for solar, wind, biomass, and small hydroelectric projects, aligning with the objectives of net zero deforestation and promotion of sustainable mobility. According to USAID, these efforts have led to the creation of 22 new solar and wind projects, increasing renewable energy generation by 2,100 megawatts and generating approximately 44,000 new jobs [70].

The assessment of the environmental impact of green hydrogen, especially in the context of its use in residential kitchens in Colombia, is presented in Table 4, providing crucial insights into its viability. The studies examined underline the need to choose sustainable production methods, considering aspects such as greenhouse gas emissions, water consumption, and technical efficiency. This analysis is of utmost importance for Colombia, a country in search of the most efficient and environmentally sustainable practices in the production of green hydrogen, in line with its natural resources and sustainability goals. Additionally, findings about the economic viability and reduction of emissions associated with green hydrogen production are particularly relevant for Colombia, alluding to a promising future in the transition to cleaner and more sustainable energies. The consideration of water consumption in this process is also critical, given the country's climatic diversity and richness in water resources.

Future research in Colombia should focus on conducting specific studies that thoroughly analyze the environmental impact of green hydrogen. This includes life cycle assessments and considerations on water usage in its production. Moreover, it is imperative to formulate specific policies that encourage the adoption of green hydrogen in the residential sector, considering both its economic viability and environmental impact. These policies should be in line with the Colombian government's efforts towards an energy transition and the promotion of clean energies. Current plans, including solar, wind, and biomass projects aimed towards the goal of net zero deforestation and sustainable mobility, reflect this approach and provide a comprehensive framework for integrating green hydrogen into the country's energy landscape. Furthermore, recognizing the transformative role of AI in the implementation and management of green hydrogen is essential. AI can be crucial in optimizing the processes of production, distribution, and use of hydrogen, as well as in overcoming technical and regulatory challenges. Its integration will allow for more informed strategic decisions and the formulation of efficient public policies, accelerating the transition to a sustainable energy model. Thus, the combination of green hydrogen and advanced technologies like AI will not only drive sustainable development in Colombia but will also set a valuable precedent for other developing economies. Recent observations suggest a growing interest and viability of green hydrogen in the energy matrix, especially in domestic applications such as cooking. Our findings provide conclusive evidence that green hydrogen is a viable and sustainable component for the future of energy.

Table 4. Long-term environmental impact assessment of green hydrogen

Evaluation criterion	Detailed analysis	Consequences for Colombia
Comparison of hydrogen production methods	The study referenced in [71] compares different hydrogen production methods, focusing on their scalability, profitability, and technical improvements. It assesses the environmental impacts of each method, including greenhouse gas emissions, water usage, land requirements, and waste generation.	This analysis is crucial for Colombia as it allows for the identification of more environmentally sustainable and efficient hydrogen production methods, taking into account the country's natural resources and sustainability goals.
Life cycle assessment of hybrid and green hydrogen models	The study referenced in [72] conducts a life cycle analysis to evaluate greenhouse gas emissions in hydrogen production. It concentrates on the transition to green hydrogen generation and its long-term economic viability.	While the study focuses on Western Canada, its findings regarding emissions reduction and economic viability are applicable to Colombia, especially in the transition to cleaner and more sustainable energy sources.
The role of water in a carbon-neutral future	The study referenced in [73] discusses water consumption in the production of various types of hydrogen, contextualizing it with other water uses and energy production. It focuses on Arizona, but the findings are relevant to regions with similar climatic conditions and water resources.	Colombia, with its climatic diversity and water resources, should carefully consider water usage in green hydrogen production, particularly in regions prone to drought or with water limitations.
Potential of alkaline water electrolysis with renewable energy	The study referenced in [74] explores hydrogen production through alkaline water electrolysis in combination with renewable energy sources. It concentrates on the feasibility and environmental impact of this technology.	This approach is particularly relevant for Colombia given its abundance of renewable resources such as solar and wind, which could facilitate more sustainable and environmentally friendly green hydrogen production.

4. CONCLUSION

Green hydrogen emerges as a crucial element in the energy transformation of Colombia, a country with significant potential to lead in its production and use due to its abundant natural resources. This resource not only promises to contribute to environmental sustainability by reducing carbon emissions but also to spur economic growth, offering new employment opportunities and technological innovation. Moreover, this energy transition directly aligns with several sustainable development goals, particularly those related to providing affordable, clean energy and promoting sustainable economic growth.

However, the effective implementation of green hydrogen in Colombia involves overcoming significant challenges. These include regulatory and legal barriers that currently hinder the development of this technology, such as the complexity in the environmental licensing process and the need to establish clear standards for low-emission hydrogen. Additionally, Colombia's ambitious goal to install up to 3,000 megawatts of electrolyzer capacity requires a considerable increase in renewable energy generation, highlighting the need to expand and adapt the existing energy infrastructure. These challenges underscore the critical importance of developing strong governmental policies and seeking international collaborations that support both the technical development and economic viability of green hydrogen.

Finally, the emphasis is placed on the need to adopt an integrated and collaborative approach to ensure sustainable and equitable progress. It is essential that future efforts focus on aligning research and development with public policies and market demands. In this way, Colombia will not only adapt to the era of green hydrogen but can also position itself as an innovative leader in this field, paving the way towards a cleaner and more sustainable energy future. This energy transformation will not only benefit Colombia but can also serve as a model for other developing economies, demonstrating that it is possible to achieve a balance between economic progress and environmental protection, in accordance with the sustainable development goals.

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APPENDIX

Table 1. Multidimensional comparison of green hydrogen production and acceptance

Research title	Aim	Major outcomes	Proposed optimizations	Study contributions	Importance	Long-term outcomes
"Cost projection of global green hydrogen production scenarios" [75]	To analyze the economic and competitive dynamics of alkaline and PEM electrolyzers in the hydrogen economy, focusing on their potential for cost reduction and global trajectories of the levelized cost of hydrogen (LCOH).	It is revealed that the economic viability and competitive advantage of alkaline and PEM electrolyzers depend significantly on potential cost reductions, with a potential cost reduction of 77% for alkaline electrolyzers and 79% for PEM electrolyzers.	The accuracy of the cost reduction trajectory depends on various factors, including the rates of system size and installed capacity growth.	The analysis indicates that the LCOH is more sensitive to variations in the electrolyzer efficiency and LCOE, emphasizing the importance of increasing efficiency and optimizing capacity factors.	An improvement in cost effectiveness in hydrogen production is suggested, although a significant reduction in LCOE, especially for onshore solar and wind energy, is required to fully exploit the potential of green hydrogen.	In optimistic scenarios, Spain could reach the LCOH target of 2 USD/kg by 2021, while in pessimistic scenarios, only China and Spain would achieve the LCOH target before 2050, highlighting the need to reduce renewable energy costs.
"The economic analysis for hydrogen production cost towards electrolyzer technologies: current and future competitiveness" [76]	To comprehensively analyze and process the production cost of hydrogen for ALK, AEM, and PEM electrolyzers through their variations in technical parameters and optima.	It is identified that the unlimited increase in current density is not an effective way to reduce the hydrogen production cost. The differences in the characteristics of hydrogen production technologies determine significant differences in the composition of hydrogen production costs.	It is suggested that increasing the service life can create significant cost reduction opportunities. Additionally, improving technical features in multiple dimensions can provide a competitive advantage.	The techno-economic model is established based on the performance of crucial materials for technical illustration and economic demonstration.	The importance of a high-capacity, low-cost electrolysis system for the significant deployment of zero-carbon hydrogen for various applications is emphasized.	The study suggests integrating renewable electricity sources, such as photovoltaic and wind energy, into the models to assess the integrated green hydrogen production chain and optimize the hydrogen energy system in real-time, aiming for the realization of a sustainable zero-carbon hydrogen society.

Table 1. Multidimensional comparison of green hydrogen production and acceptance (*continue…*)

Research Title	Aim	Major outcomes	Proposed optimizations	Study contributions	Importance	Long-term outcomes
"Green Hydrogen for Karnataka: Regional Solutions for a Clean Energy Future" [77]	Examine meticulously the challenges and barriers that Karnataka faces in the implementation of green hydrogen.	Karnataka has emerged as a leader in the adoption of green hydrogen, setting a precedent for sustainable energy transitions.	Innovative solutions have been proposed to overcome technical, economic, regulatory, and infrastructure challenges, with an emphasis on the creation of regional hydrogen clusters.	Karnataka's collaborative approach involves government entities, industry stakeholders, and researchers, serving as a model for innovation, economic growth, and environmental sustainability.	Karnataka's commitment to green hydrogen adoption provides valuable insights and lessons for regions undertaking similar energy transitions.	The success of Karnataka's green hydrogen initiatives depends on continuous commitment, policy support, and attracting investments, contributing significantly to the global mission of combating climate change and transitioning to a cleaner and more sustainable energy ecosystem.
"Can hydrogen be the sustainable fuel for mobility in India in the global context?" [78]	Provide a holistic assessment of the significance of hydrogen as a fuel for sustainable mobility from an Indian perspective.	Hydrogen-based vehicles offer numerous advantages compared to battery electric vehicles, especially in terms of charging time, range anxiety, high power density, and lower well-to-wheel energy, in addition to being sustainable.	Increasing the number of production units can substantially reduce production costs. Market penetration strategies will play an integral role in rapid commercialization.	The use of hydrogen and fuel cell technologies is still in development, and collaboration between industries, manufacturers, governments, and safety professionals is key to developing and establishing technically competent regulations and standards.	Hydrogen as a fuel for sustainable mobility is significantly advantageous compared to battery electric vehicles and traditional internal combustion vehicles, although it still faces challenges with storage infrastructure.	Strict government policies and ongoing projects will be a promising solution to overcome associated challenges; therefore, hydrogen is potentially a sustainable fuel for mobility, not in the long term, but in the short term.
"Improving green hydrogen production from Chlorella vulgaris via formic acid-mediated hydrothermal carbonisation and neural network modelling" [79]	Examine an alternative scenario for biomass to green hydrogen synthesis using acid-mediated hydrothermal carbonization (HTC).	The production of hydrogen and total HTC gas was significantly improved and modeled alongside the formation and characteristics of hydrochar and HTC liquid using machine learning tools. Harsher conditions increase the evolution of H_2, CO_2, and CO.	The interaction between the combined severity factor and feed suspension ratio parameters influencing HTC product formation is identified.	Hydrogen production under moderate reaction conditions offers energy-saving benefits over high-temperature thermochemical conversion methods.	The study provides an alternative pathway for green hydrogen production that is more energy-efficient compared to traditional high-temperature thermochemical methods.	The presented approach offers potential energy-saving benefits and may influence future research and industrial applications for sustainable hydrogen production.

Table 1. Multidimensional comparison of green hydrogen production and acceptance (*continue…*)

Research Title	Aim	Major outcomes	Proposed optimizations	Study contributions	Importance	Long-term outcomes
"Gauging public perceptions of blue and green hydrogen futures: Is the twin-track approach compatible with hydrogen acceptance?" [80]	Focus on various key aspects of domestic hydrogen acceptance, including consumer preferences regarding hydrogen production pathways, change logistics, and information processes.	Relatively low levels of knowledge and awareness about hydrogen; hydrogen transport applications are better known than other use cases; and men over 30 are the most informed demographic group.	A more detailed and comparative nationwide study is suggested to validate the qualitative findings of this study. The use of structural equation models is advocated to explore and validate the antecedents of hydrogen acceptance.	Reveals more nuanced findings that link hydrogen engagement levels to observed generational gaps. Additionally, location appears to influence consumer perspectives.	The results can be transferred to other countries considering a hydrogen transition pathway similar to the UK's and pioneering nations exploring the merits of different hydrogen production pathways.	There are serious doubts about whether the dual-pathway approach, as currently understood by the public, will be compatible with hydrogen acceptance at both the socio-political and individual levels.

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